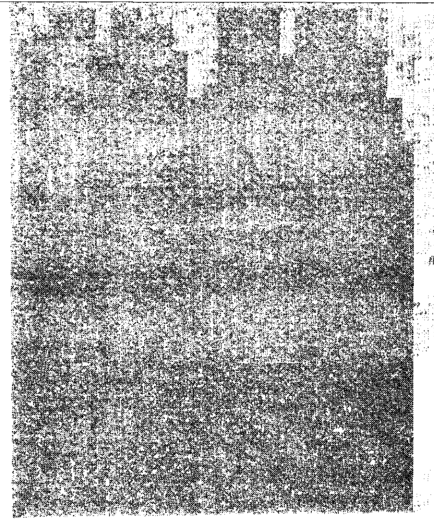
A Study of Trends in Total Phosphorus Measurements at NASQAN Stations



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A Study of Trends in Total Phosphorus Measurements at NASQAN Stations

By RICHARD A. SMITH, ROBERT M. HIRSCH, and JAMES R. SLACK

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A Study of Trends in Total Phosphorus Measurements at NASQAN Stations

By Richard A. Smith, Robert M. Hirsch, and James R. Slack

Abstract

A new test for trend, called the Seasonal Kendall test, is defined. The test is shown to have properties that make it suitable for detecting trends in water-quality data. As a demonstration, the test is applied to 5- to 8-year time series of total phosphorus data collected monthly at more than 300 stations in the National Stream Quality Accounting Network (NASQAN). The test is applied to time series of concentration values, instantaneous transport (load) values, and flow-adjusted concentrations. Flow-adjusted concentrations are defined as the residuals from a regression of concentration on a function of stream discharge. For each station, the regression function is selected from among eleven possible relationships on the basis of R^2 value.

Under two different significance criteria ($\alpha=0.10$ and $\alpha=0.01$, two-tailed), significant trends are observed at far more NASQAN stations than would be expected by chance alone. Of 303 stations tested for trends in phosphorus concentration, 38 showed significant ($\alpha=0.10$) uptrends and 62 showed significant downtrends. Of 289 stations tested for trends in transport rate, 62 showed significant downtrends and only 23 showed significant uptrends. Trend tests on flow-adjusted concentrations were significantly different from trend tests on unadjusted concentration data; 45 stations showed significant downtrends and 40 showed significant uptrends.

INTRODUCTION

The National Stream Quality Accounting Network (NASQAN) is currently a set of 517 stations at which a large number of water-quality characteristics of rivers are measured regularly. The major objectives of this U.S. Geological Survey program are (1) to account for the quantity and quality of water moving within and from the United States; (2) to depict the areal variability of stream quality; (3) to depict the temporal variability of stream quality; and (4) to detect long-term trends in stream quality.

The need for a national program such as NASQAN was discussed by Wolman (1971) who, in an assessment of the state of the nation's rivers, noted that data suitable for determining long-term trends in stream quality were relatively sparse. Wolman pointed out some of the problems in the statistical analysis of existing stream-quality data: (1) existing records were short; (2) frequency, location or measurement methods have changed; (3) important correlative data such as streamflow, temperature, and conductivity was not always collected when chemical or biological analyses were made; and (4) the sampling plan was not adequate to characterize the temporal variability of stream quality. Enviro Control (1972), and Steele and others (1974), noted a regional imbalance in the number of long-term stations (more in the northeastern and northwestern regions, fewer in the northcentral and southeastern regions). NASQAN was instituted as a Geological Survey program in 1972 as a response to these problems. The number of stations has grown over the succeeding years from 50 stations in January 1973 to 345 in September 1975 to 517 in 1980. The NASQAN data collection schedule is given in table 1. The use of a fixed-sampling schedule (rather than one that is governed by hydrologic conditions) makes NASQAN particularly suited to the depiction of variability and the detection of trends. The stations are located predominately on large rivers, but are not specifically chosen to monitor conditions in known problem areas; other networks exist for this purpose. (Monitoring specific problem areas requires individually designed monitoring plans.) It provides a large and diverse data base to be queried as new scientific or national policy questions arise.

This report dealing with total phosphorus is an attempt to compile a national summary of stream-quality trends using NASQAN data. The intent of this report is to demonstrate methods to (1) identify individual stations at which long-term trends in phosphorus concentration or transport may be occurring; and (2) summarize these trends regionally and nationally. Trend is taken to mean systematic monotonic change in the data over time (that is, correlation with time). It is the authors' hope that this work will interest other investigators in searching for causes or explanations of the individual station, regional, and national results presented here.

PHOSPHORUS DATA

Total Phosphorus Measurements

Total phosphorus measurements in the NASQAN program are made with whole water samples and thus include all forms of phosphorus—suspended, dissolved,

Table 1. Characteristics measured at NASQAN stations

[Frequencies: *C*, continuous; *D*, daily; *M*, monthly; *Q*, quarterly]

	Frequency
Field determinations:	
Water temperature	[1]*C*, *D*, or *M*
Specific conductance	[1]*C*, *D*, or *M*
Dissolved oxygen	*M*
pH	*M*
Discharge	*C*
Coliform, fecal	*M*
Streptococci, fecal	*M*
Common constituents (dissolved)[2]	*M* or *Q*
(Bicarbonate, carbonate, total hardness, noncarbonate hardness, calcium, magnesium, fluoride, sodium, potassium, dissolved solids, silica, turbidity, chloride, and sulfate).	
Major nutrients (total and dissolved)	*M*
(Phosphorus, nitrite plus nitrate, Kjeldahl nitrogen, ammonia nitrogen, and organic nitrogen).	
Trace elements (total and dissolved)	*Q*
(Arsenic, cadmium, chromium, cobalt, copper, iron, lead, manganese, mercury, selenium, barium, silver, nickel, and zinc).	
Organic and biological constituents:	
Organic carbon, total	8/Yr
Phytoplankton, total, cells/mL	7/Yr
Phytoplankton, identification of three codominants	7/Yr
Phytoplankton, three codominants, percent of total	7/Yr
Periphyton, biomass, dry weight g/m^2	*Q*
Periphyton, biomass, ash weight g/m^2	*Q*
Periphyton, chlorophyll α	*Q*
Periphyton, chlorophyll β	*Q*
Suspended sediment:	
Suspended sediment concentration	*M*
Percent finer than 0.062-mm sieve diameter	*M*

[1] Continuous or daily, depending upon whether the station is equipped with a monitor or whether daily observations are made. Monthly measurements made at stations where a long-term record is available.

[2] Dissolved constituents in water are those remaining after filtering samples through 0.45-μm membrane filters.

organic, and inorganic. The phosphomolybdate method following acid digestion (Skougstad and others, 1979) is used in laboratory analysis. The detection limit is 0.01 mg/L as phosphorus.

Significance of Phosphorus in Natural Waters

Phosphorus in streams is contributed from a number of sources, both cultural and natural. Some of the more important of these are breakdown and erosion of phosphorus-bearing minerals in the soil, decaying plant and animal material, agricultural and domestic fertilizers, synthetic detergents, treated sewage effluents, and leaking septic systems. In streams carrying large sediment loads, total phosphorus concentrations are often positively correlated with suspended solids concentrations, due to the tendency for inorganic phosphorus to adsorb to sediment particles.

Concern for the level of phosphorus in streams is based primarily on the role of phosphorus in promoting eutrophication. Of the major nutrients, phosphorus is the one most frequently found to be limiting to plant growth in nonmarine waters. Phytoplankton densities in lakes, for example, have been shown to be predictable on the basis of total phosphorus loads of tributary streams (Sakamoto, 1966; Dillon and Rigler, 1974).

Phosphorus Standards

Despite the strong correlation between total phosphorus concentration and eutrophication, there is no widespread agreement on acceptable levels of total phosphorus in streams, due largely to the absence of universal standards on what constitutes eutrophic conditions. The U.S. Environmental Protection Agency "Quality Criteria for Water" (1976) suggests 0.05 mg/L as an upper limit on total phosphorus in lake tributaries, and 0.1 mg/L as an upper limit for preventing nuisance growths in streams not flowing directly into lakes.

The Data Set

The data used in this study are a subset of the available NASQAN total phosphorus data. They consist of data collected in the years 1972 thru 1979 from stations in operation from 1975 thru 1979. The 308 stations meeting this criterion are listed in table A in appendix A. The locations of these stations in the 48 conterminous States are shown in figure 1.

A total of 303 stations had records with at least 24 observations and were used in trend testing (see below). Phosphorus is sampled monthly at most NASQAN stations. The test applied is designed for time series of monthly values (with possible missing values), observations in excess of one each month were ignored. When more than one observation was available in a month, the earliest observation with a companion discharge value was used; lacking any discharge data, the earliest observation was used. For each observation for which both constituent and discharge values were available, a transport rate in tons per day was computed as the product of the concentration and the discharge and multiplied by 0.002697 to express transport in units of tons per day.

There is a dilemma in deciding how long a record to use in trend testing. A trend which now exists may have existed for only a few years and may even be a reversal of a previous trend. The use of a long record tends to mask a current trend. On the other hand, a very short record may not contain enough data to distinguish a trend from natural variability in the data. The above criteria for selecting data represent a reasonable but arbitrary choice of record length for trend testing.

METHODS

Trend Detection: Existing Problems

Simply put, hypothesis testing for trend detection consists of the following steps:

a. State the null hypothesis and background assumptions for the test (an example of a null hypothesis might be: the random variable and its time of observation are independent. An example of background assumptions could be that the random variable is serially independent and normally distributed);
b. Calculate an appropriate test statistic from the data;
c. Interpret the value of the statistic in light of the known probability distribution of the statistic;
d. If the value of the test statistic is within preselected limits on the distribution, accept the null hypothesis; or,
e. If the value of the test statistic is outside the preselected limits, the null hypothesis cannot be accepted and a "statistically significant trend" is claimed.

The limits are calculated from a preselected probability—typically denoted by the Greek letter alpha (α)—such that the probability that the test statistic would fall outside the limits is α if the null hypothesis and all background assumptions were true. A typical value selected for α is 0.1. Then one may say that a trend is, or is not, statistically significant at the 10 percent level. That

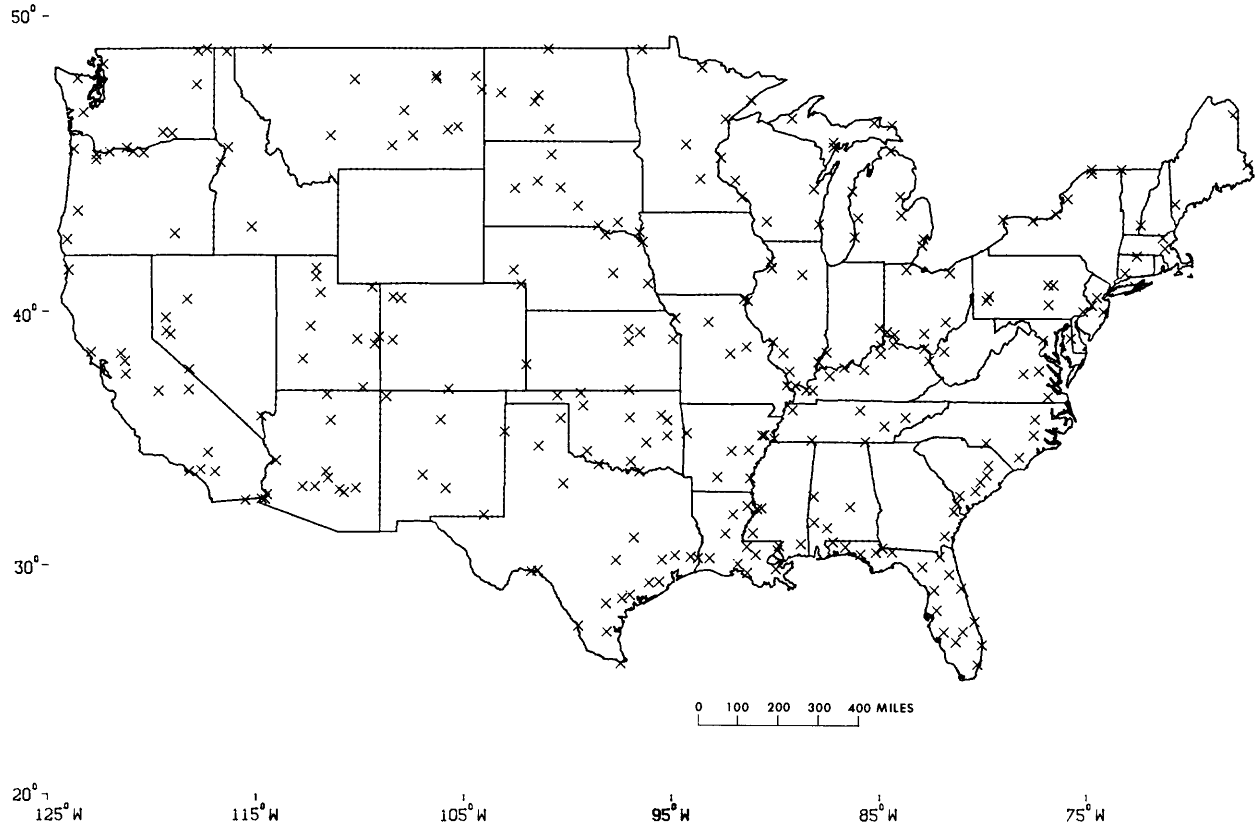

Figure 1. The locations of NASQAN stations in the 48 conterminous States.

is, in 90 percent of the cases, one will correctly say there is no trend when such is true. One may also report test results by a probability value (denoted p). This is the probability that the test statistic would depart from its expectation by at least the observed amount, under the null hypothesis.

For a hypothesis test to be valid, the probability distribution of the test statistic must be known. Rarely, however, is the distribution known in practice. The real world rarely behaves as nicely as statistical textbooks would have it. The underlying random mechanism of a natural phenomenon is largely unknowable and yet it is necessary to have some information (not necessarily a complete specification) on the mechanism in order to know the probability distribution of the test statistic. And even if one could know that the mechanism is of a particular type, arriving at the distribution of the test statistic analytically may be very difficult, if not impossible. One may select a test which is very powerful under certain very restrictive assumptions or a test which is slightly less powerful under those assumptions, but corresponds better to our fuzzy understanding of the world. A major goal of this study is to demonstrate a straightforward test which maintains a good ability to detect trends under a wide range of anticipated conditions.

One common test for trend is based on linear regression of the variable of interest against time. The null hypothesis is that the variable and time are uncorrelated, and the background assumptions are that the data are normal, independent, and identically distributed in time. If the slope of the regression equation is found to be statistically significant, a trend is claimed. Unfortunately, several of the assumptions underlying the derivation of the necessary probability distribution to test for significance are violated by natural data such as we are considering here. In general, water-quality data have seasonality, are skewed, and are serially correlated. These features contradict the assumptions of stationarity, normality, and independence of the random variable (the water-quality variable) required for computing the probability distribution of the test statistic in the regression test for trend. The seasonality inflates the variance used in the t-tests, the skewness increases the standard error in the estimated slope, and the serial correlation raises the actual α level relative to the selected α level. Any one of these defects may be sufficient to render the test invalid, especially since the amount by which they are present—and therefore, the amount by which the test is being distorted—cannot be known.

The same or similar objections can be raised against virtually every test for trend when applied to almost any water-quality variable. Attempts have been made to alter (transform) the data to remove or reduce the undesirable features. To remove seasonality, one might fit a sine curve to the data (Steele and others, 1974) and use the deviations from the curve as the random variable to be tested. But with the exception of a few variables such as water temperature, there is little reason to believe that the form of seasonality is a pure sine curve. The extent to which the cure works is largely unknowable. To eliminate skewness, one might use the logarithms of the data. Again, the extent to which this is proper is only a guess. Compensating for serial correlation is at best an art. Trying to do all three is extremely difficult, if not impossible. What is needed is a test that is largely unaffected by the three above-mentioned characteristics of the data. That is, the distribution of the test statistic is influenced little by these three characteristics of the data.

The Seasonal Kendall Test

Statistical tests may be classified as classical or distribution-free (Bradley, 1968). Classical tests, such as those used in regression, require the estimation of one or more parameters (for example, the slope of the regression line) based on the observed values of the variable and the distribution of the test statistic under the null hypothesis follows from an assumption about the underlying probability distribution of the random variable.

Distribution-free tests typically ignore the magnitudes of the data in favor of the relative values or ranks of the data. The major advantage of distribution-free tests is that the underlying probability distribution of the random variable is immaterial. In fact, any strictly increasing monotonic transformation—such as taking logarithms—changes the values of the data, but does not affect the relative rankings. However, because the magnitudes are ignored, the test provides only a yes-or-no, not a how-much, answer.

The distribution-free test which serves as the basis for trend testing in this study is Kendall's Tau (Kendall, 1975). The null hypothesis for this test is that the random variable is independent of time. The only necessary background assumption is that the random variable is independent and identically distributed (with any distribution). In this test, all possible pairs of data values are compared; if the later value (in time) is higher, a plus is scored; if the later value is lower, a minus is scored. If there is no trend in the data, the odds are 50–50 that a value is higher (or lower) than one of its predecessors. In the absence of a trend, the number of pluses should be about the same as the number of minuses. If, however, there are many more pluses than minuses, the values later in the series are more frequently higher than those earlier in the series, and so an uptrend is likely. Similarly, if there are many more minuses than pluses, a downtrend is likely.

As discussed above, the one common pattern to water-quality variables is that they have a period of one year (other periodicities may exist). Comparing, for example, a January value with a May value does not contribute any information about the existence of a trend, if a seasonal cycle of a 1-year period exists. Thus, we define the Seasonal Kendall test to be the Kendall's Tau test restricted to those pairs of data which are multiples of 12 months apart. Since comparisons are made only between data from the same month of the year, the problem of seasonality is avoided. Thus, the background assumptions given above are relaxed. The random variable may be nonidentically distributed, provided that the distributions 12 months apart are identical. A complete specification of the Seasonal Kendall test is given in appendix B. Its derivation is given by Hirsch and others (1982).

When all of the assumptions for the regression test are met, the regression test is the most powerful test for linear trend (Kendall and Stuart, 1973, p. 499). The Seasonal Kendall test is shown to be almost as powerful, based on a series of tests using generated random numbers (Hirsch and others, 1982). When skewness or seasonality were introduced in the experiments, the Seasonal Kendall test performed better than the test based on linear regression; and when serial correlation was introduced, its effect on the Seasonal Kendall test was no more severe than its effect on linear regression. In particular, where the generating process has serial dependence, the probability of obtaining a positive test for trend, when the process is not changing over time, is higher than the preselected probability, α.

The Seasonal Kendall Slope Estimator

In addition to indicating whether a trend exists, it may be desirable to estimate the magnitude of such a trend. This magnitude is expressed here as a slope (value per unit time), although this does not imply that a linear trend is assumed. As a companion to the Seasonal Kendall test, we define the Seasonal Kendall Slope Estimator (Hirsch and others, 1982) to be the median of the differences (expressed as slopes) of the ordered pairs of data values that are compared in the Seasonal Kendall test. Instead of recording a plus or minus for each comparison, one simply records the difference divided by the number of years separating the data points. The median of these differences is taken to be the change per year due to the trend. In particular, if the linear function of time with this slope is subtracted from each data value, a subsequent application of the Seasonal Kendall Slope Estimator to the (residual) series will yield the "perfect" no-trend result of zero slope. A demonstration of this is shown in appendix B.

Flow-Adjustment Procedure

It is well known that in many streams, total phosphorus concentrations are related to stream discharge (Hobbie and Likens, 1973; Borman and others, 1974; or Reckhow, 1978). This relationship can be rather complex in some streams. At base flow conditions, much of the phosphorus may be from point-source loadings. Thus, any decrease in flow would tend to be accompanied by increases in concentration. On the other hand, the occurrence of a large rainstorm over the drainage basin may cause the erosion and transport of substantial amounts of organic material and soil particles which carry considerable phosphorus. Thus, increases in flow may bring about increased phosphorus concentrations. Depending on the relative importance of these two processes (dilution and erosion), the slope of the relationship of discharge and phosphorus concentration may be negative, positive, or perhaps both (as in a parabola). Figures 2A and 2B provide examples of these relationships. The Klamath River of California (fig. 2A) is a stream with relatively high sediment concentrations. In this instance, the importance of soil erosion and transport as a contributor to phosphorus concentration is paramount. In contrast, the Black River in South Carolina (fig. 2B) has much lower sediment concentrations and exhibits a pattern typical of dilution. Whichever type of relationship exists, it is clear that the understanding of this relationship is vital to the analysis and interpretation of stream quality.

Consider, for example, a stream where the discharge versus phosphorus concentration relationship is positive (dominated by soil erosion and transport) and that during the earlier years of record there was a prolonged drought and in the later years, a prolonged period of wet weather. Here, one would expect to find an upward trend in phosphorus concentration. Assuming further that there have been no changes in land-use practices (no change in soil erosion, pollution mitigation practices, or fertilizer applications), one would then expect a return to more normal phosphorus concentrations when the wet weather period ends.

Thus, one may want not only to identify trends in concentration or transport, but also to determine if there is a change in the processes that cause phosphorus to enter the stream. Such processes may include: point-source loading rates, methods and amounts of phosphorus fertilizer applications, erosion-control measures in agriculture, silviculture or construction, or rates of forest harvesting, to name a few possibilities.

The approach used here to identify such process trends is to develop a time series of flow-adjusted concentrations (*FAC*) and test this time series for trend. This technique is generally referred to as residual analysis. For

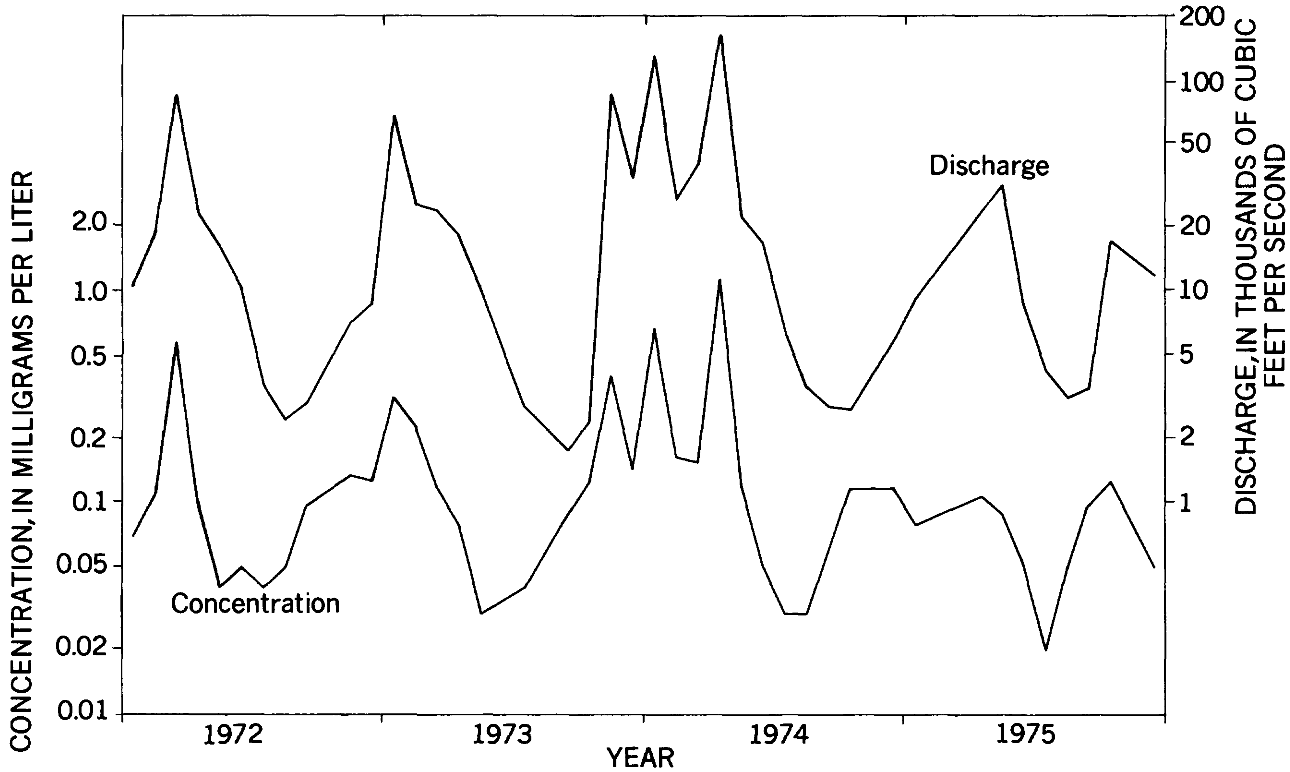

Figure 2A. Discharge and total phosphorus concentration, Klamath River near Klamath, California, 1972–75.

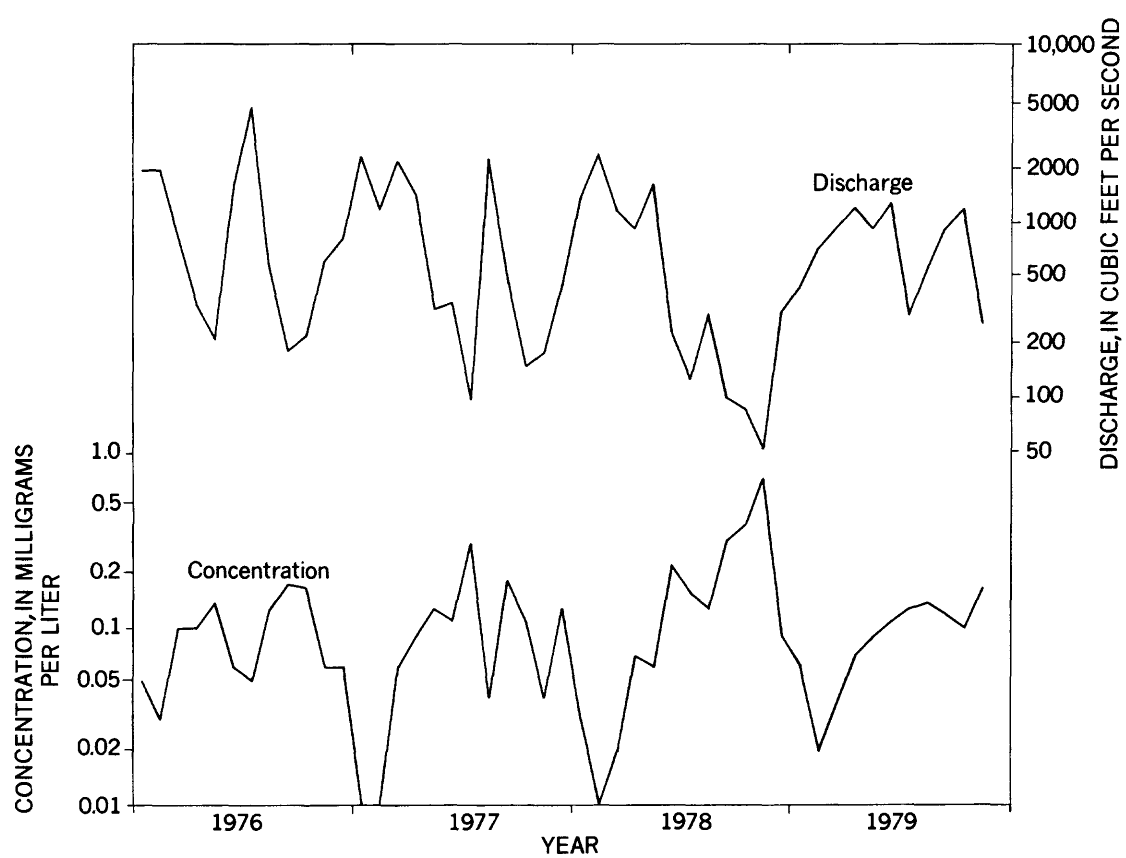

Figure 2B. Discharge and total phosphorus concentration, Black River at Kingstree, South Carolina, 1976–80.

each stream, the relationship between discharge and phosphorus concentration is estimated and used to provide a conditional expected value of concentration for every flow value. We define *FAC* as the actual concentration minus the estimated conditional expected concentration. If the process has not changed over the period of record, then one would expect the *FAC* values to fluctuate randomly about zero over the period of record. If there has been a change during the period of record, say a major new source (or elimination of a source) of phosphorus in the river basin, then one would expect to see an upward (or downward) trend in *FAC* with a preponderance of negative (or positive) values at the beginning and positive (or negative) values at the end.

In summary, trends in concentration or transport may arise either as a consequence of the particular sequence of flow conditions sampled or as a consequence of some change in the processes which supply phosphorus to the stream (or some combination of the two). The analysis of trends in *FAC* is an attempt to identify only those stations where some process (source) change has occurred.

The relationship between discharge and concentration is expressed in this study as a flow-adjustment equation of the form:

$$\hat{C} = a + b \cdot f(Q) \qquad (1)$$

where $\hat{C}$ is the estimated concentration, Q is the instantaneous discharge, and $f(Q)$ may have one of the following forms:

Functional Form	*Name*	
$f(Q) = Q$	linear	(2a)
$f(Q) = \ln Q$	log	(2b)
$f(Q) = \frac{1}{1+\beta Q}$	*hyperbolic	(2c)
$f(Q) = \frac{1}{Q}$	inverse	(2d)

*where β is a positive constant.

The function (2c) was introduced by Johnson and others (1969) specifically for describing the behavior of the dissolved major ion species. It is included here, along with the other more common model forms 2a, 2b, and 2d, because of its considerable flexibility and demonstrated usefulness with many constituents.

The choice of the particular functional form and the estimation of the coefficients a, b, and β (where needed) was carried out in the following fashion for each of the 289 stations at which there were more than 24 pairs of total phosphorus concentration and concurrent instantaneous discharge values:

1. Using linear regression (*LR*), estimate the coefficients a and b of $\hat{C} = a + bQ$, and compute R^2 and p. R^2 is the fraction of the variance explained and p is the probability of erroneously rejecting the null hypothesis (that $b = o$).
2. Using *LR*, estimate the coefficient a and b of $\hat{C} = a + b \ln(Q)$ and compute R^2 and p.
3. Determine the average Q value, $\bar{Q}$.
4. Find the integer part (characteristic) of $\log_{10} \bar{Q}$ call it β^*.
5. Set $\beta = 10^{-2.5\ \beta^*}$.
6. Using *LR*, estimate the coefficient a and b in $\hat{C} = a + b \cdot \frac{1}{1+\beta Q}$ and compute R^2 and p.
7. Increment the value of β by multiplying by $10^{0.5}$
8. If $\beta = 10^{1.5-\beta^*}$, go to step 9. If not, go to step 6.
9. Using *LR*, estimate the coefficient a and b of $\hat{C} = a + b \cdot \frac{1}{Q}$ and compute R^2 and p.
10. At this point, 11 regression equations have been estimated. The one with the highest R^2 value will be used to perform the flow adjustment.

If all 11 relationships are very poor ($p > 0.10$) or if fewer than 24 discharge values were available, then the flow-adjustment equation is:

$$\hat{C} = \bar{C}$$

where $\bar{C}$ is the average concentration. Figures 3A and 3B show some examples of these fitted relationships.

The time series of *FAC* values is computed for every station. It should be noted that the number of *FAC* values will be less than the number of concentration values, if some discharge values are missing.

RESULTS AND DISCUSSION

Statistics Reported

Summary statistics derived from the data are displayed in table A in appendix A. The mean concentrations of total phosphorus are expressed in mg/L. The values shown are the arithmetic averages of the observations for each station. Because no adjustment was made for months without a value, the mean for a station with missing values is not a time-weighted mean, but simply a sample mean. Mean concentrations are displayed graphically on the map in figure 4. The mean of the discharge observations used in cubic feet per second is also listed in table A. The average of these transport values is listed in table A for each station and displayed on the map in figure 5. A discharge weighted mean concentration can be calculated by dividing the mean transport by the mean discharge and multiplying the product by 370.78 to express the concentration in mg/L.

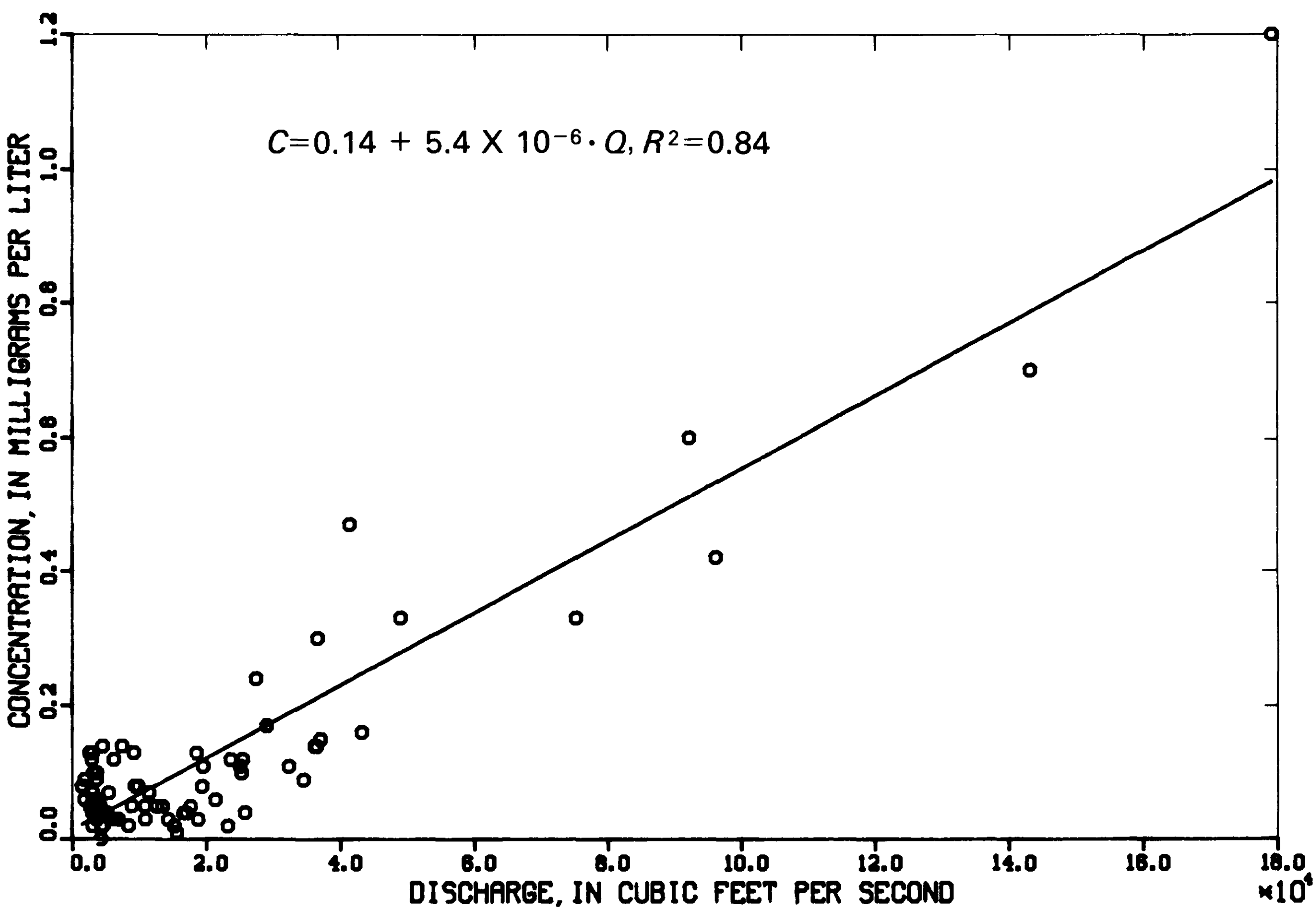

Figure 3A. Relationship between discharge and total phosphorus concentration, Klamath River near Klamath, California.

The Seasonal Kendall test and the Seasonal Kendall Slope Estimator were applied to the following time series (selected on the basis of having more than 24 observations):

(1) Time series of total phosphorus concentrations at 303 stations,

(2) Time series of total phosphorus transport values at 289 stations, and

(3) Time series of flow adjusted concentrations (*FAC*) at 303 stations.

At 99 of these 303 stations, the trend test results on the concentration values and the *FAC* values are, by construction, identical because the relationship $\hat{C}=\bar{C}$ was used. These 99 stations had either insufficient discharge data or too poor a discharge-versus-concentration relationship to warrant use of a flow-adjustment equation. The primary information derived from the Seasonal Kendall procedures for each time series is the α level and the trend slope in milligrams per liter (mg/L) per year (for concentration or *FAC*) or tons per day per year (for transport). Along with this information in table A is information about the discharge-versus-concentration relationship.

Mean Concentrations

As indicated by the map in figure 4, mean concentrations of total *P* display wide geographic variation. High values (greater than 1.0 mg/L) occur frequently in the Southwest and at selected locations in the Missouri and Colorado basins, along the Texas Gulf Coast, and in

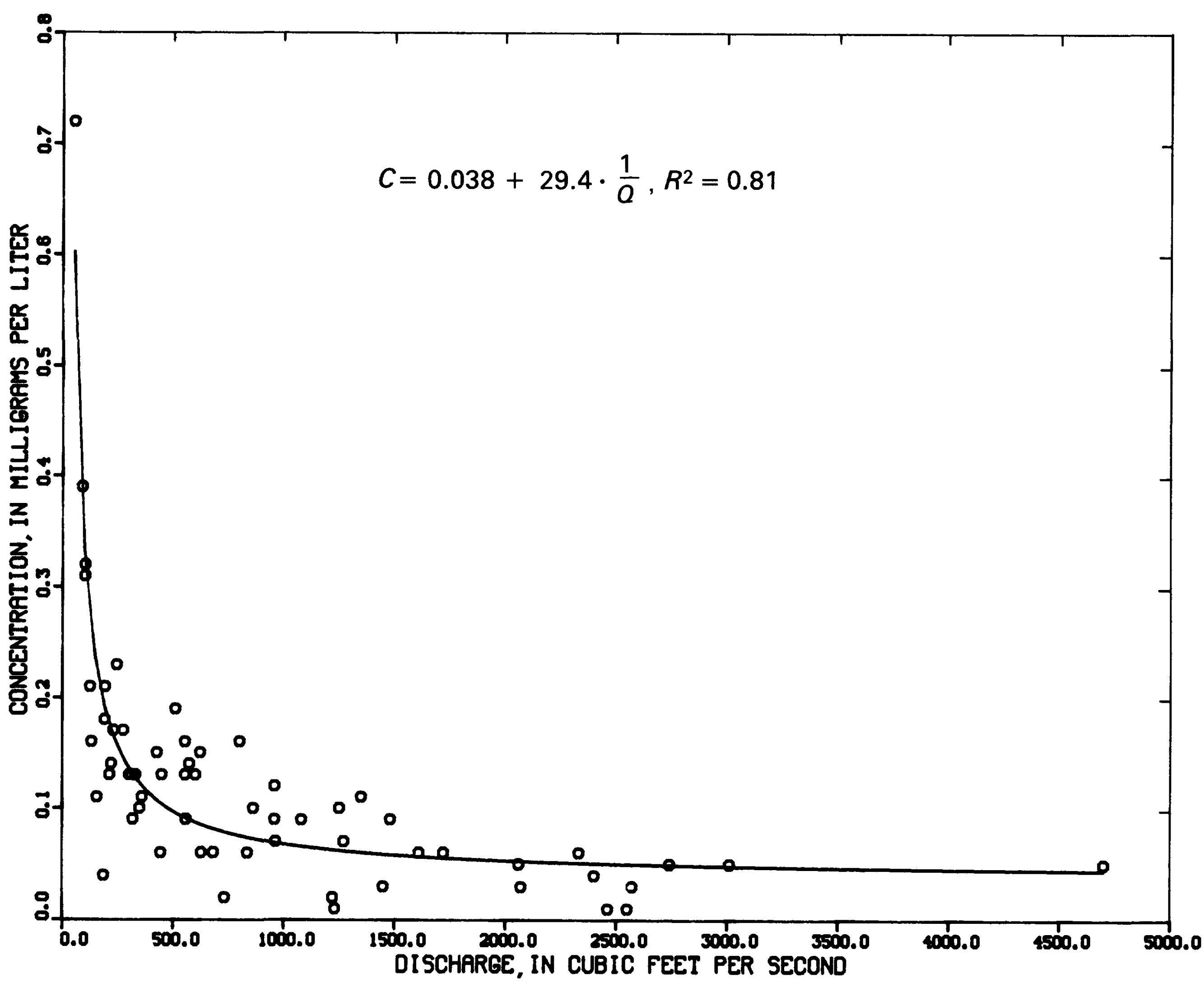

Figure 3B. Relationship between discharge and total phosphorus concentration, Black River at Kingstree, South Carolina.

western Florida near major deposits of phosphate rock. In much of the Midwest, and in agricultural areas in general, concentrations typically fall in the range of 0.1 to 1.0 mg/L. Mean concentrations less than 0.1 mg/L are largely restricted to forested and remote basins.

Mean Transport Levels

The geographic distribution of total phosphorus transport is notably different from the geographic distribution of mean concentration and provides a much clearer picture of phosphorus loading rates. Transport is highest in regions of high precipitation including the Great Lakes, Susquehanna, Ohio, and Columbia basins where concentrations are low to moderate, and is low in the Southwest where concentrations are highest. Since wet, high runoff regions of the country also correspond to a large degree with levels of agricultural and industrial activity, the geographic pattern in phosphorus transport is not surprising.

A further pattern observable in figure 5 is the tendency for total phosphorus transport to increase progressively along the course of the major drainage systems. The pattern is evidence that total phosphorus transport is relatively conservative, despite the biological activity of dissolved forms and the tendency for phosphorus to adsorb to sediment particles.

Concentration-Flow Relationship

Of 289 regressions between total phosphorus concentration and streamflow, 204 gave "significant" results

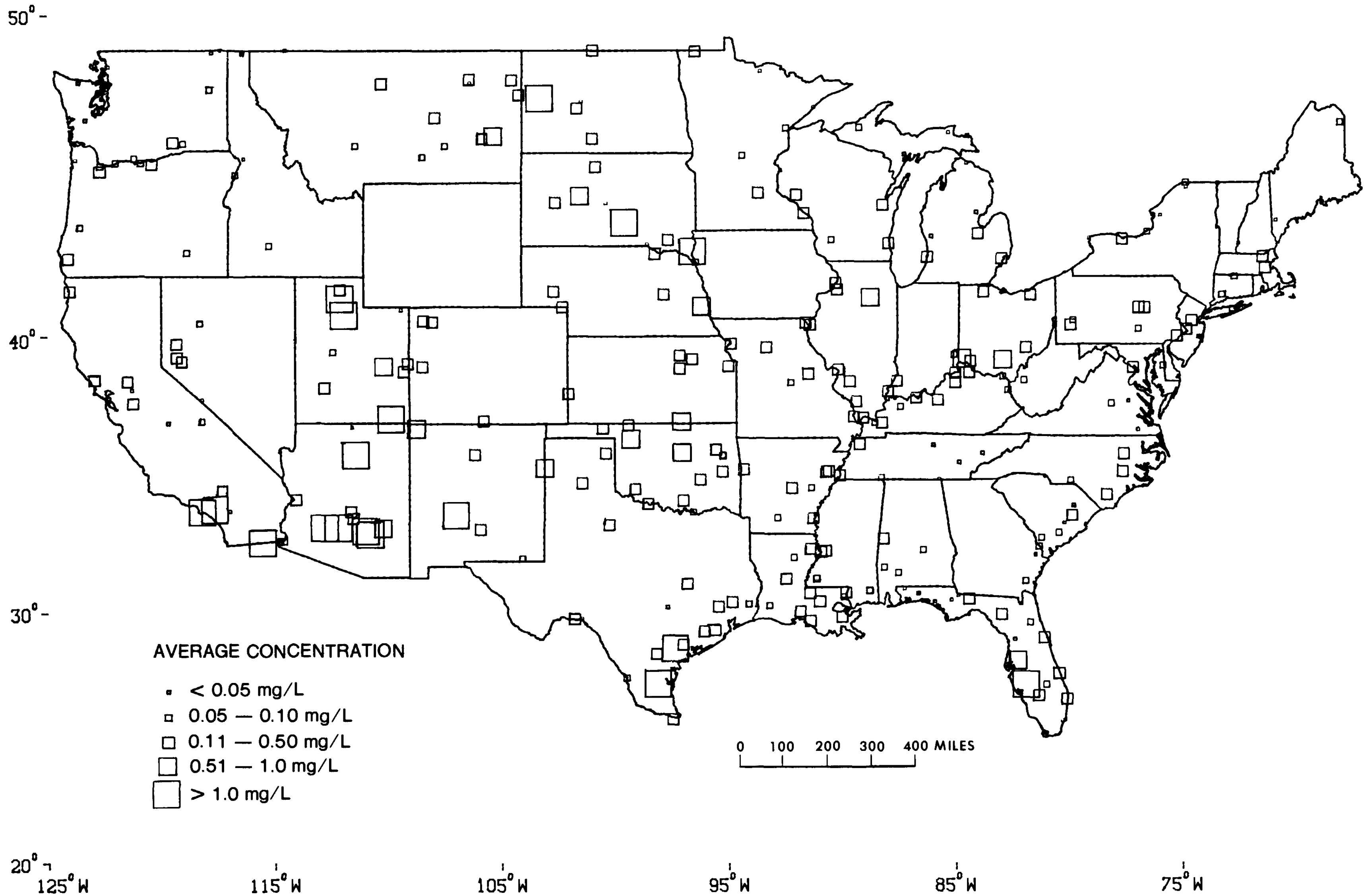

Figure 4. Average total phosphorus concentration.

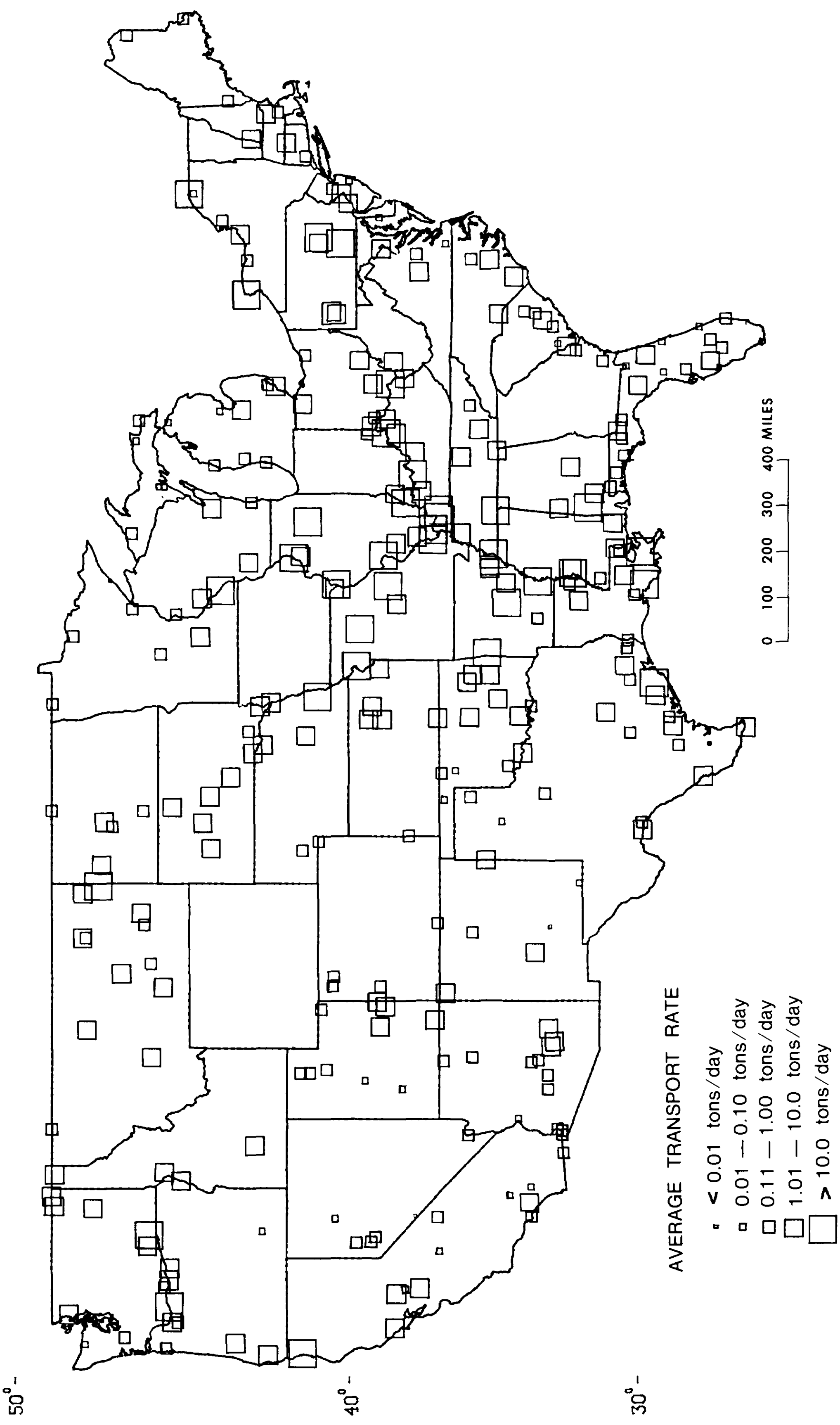

Figure 5. Average transport rate for total phosphorus.

based on the criterion $p \leq 0.1$, and, of these, 158 regressions were found to be "highly significant" based on the criterion $p \leq 0.01$ (fig. 6). Of the 204 "significant" regressions, the best functional forms were linear in 41 cases, logarithmic in 8 cases, hyperbolic in 127 cases, and inverse in 28 cases. The choice of significance criteria is admittedly somewhat arbitrary. Nevertheless, some decision must be made on when regressions are strong enough to warrant further consideration. In cases where p was greater than 0.1, regression results were not used to make flow adjustments for trend analyses.

One particularly interesting feature of figure 6 is the occurrence of significant positive as well as significant negative correlations between flow and concentration at NASQAN stations. In 147 cases, the slope of the discharge versus total phosphorus concentration relationship was positive, indicating that erosion and transport of total phosphorus at high flows was the dominant process. In 57 cases, the slope was negative, indicating that dilution (of point-source contributions or of subsurface dissolved phosphorus sources) was the dominant process. Many of the stations immediately below large reservoirs show poor ($p > 0.10$) relationships because the discharge is, in large part, the consequence of a human decision which would generally not be related to the reservoir phosphorus concentration. Nationwide, negative relationships between total phosphorus and flow occur far less frequently than do positive relationships, and appear to be limited to forested basins along the East Coast, in the Great Lakes drainage, and in California.

While regression p values provide an appropriate basis for deciding when to make adjustments for flow dependence, a measure of the predictability of concentration on the basis of flow is given by the proportion of variance explained, or R^2. Of 289 regressions, approximately one-third had R^2 values greater than 0.25. Figure 7 is a histogram of R^2 values for the 289 stations. A complete reporting of R^2 values is contained in table A.

Results of Trend Procedures

Figures 8, 9, and 10 provide the salient features of the results of the Seasonal Kendall procedures for concentration, transport, and *FAC* for the 48 conterminous States. The results are summarized in tabular form in tables 2 and 3. The first of these takes $\alpha = 0.10$ as indicative of a significant trend and the latter takes $\alpha = 0.01$ as indicative of a significant trend. Using either of these trend criteria, the proportion of stations exhibiting significant trends was substantially more than α, the proportion that would be expected to show trends by chance alone. The expected proportion of stations showing trend by chance alone is not affected by the existence of spatial dependence. It should be recognized that the null hypothesis subsumes the condition that the data be serially independent. It is known that the data are not independent, but the estimation of the pattern of serial dependence (correlogram) is made difficult by the seasonality and skewness of the data, by the shortness of the records, and by the possibility that process changes have, in fact, occurred during the period of record. Paradoxically, one must know about the serial correlations to perform a trend test that compensates properly for correlation, and it is necessary to know about the trend in order to estimate the serial correlation. Understanding the serial correlation structure of total phosphorus data (indeed of all water-quality data) is an important area for research. It may be that a good deal of the correlation in concentration or transport data arises from the serial correlation of the discharges. Thus, the trend tests on *FAC* may be less prone to identifying trends where serial correlation or long-term persistence, rather than underlying changes, have given the concentration or transport data the appearance of a trend.

Consider, for example, the trend tests on the three time-series (concentration, transport, and *FAC*) for the Klamath River near Klamath, California (station number 11530500, drainage area 12,100 square miles). Figure 11A shows the record of total phosphorus concentrations. The average concentration of total phosphorus was 0.12 mg/L and the standard deviation was 0.17 mg/L. The trend test indicates a highly significant ($p = 0.006$) downward trend. The slope estimate is -0.005 mg/L per year or -4.1 percent of the mean per year. The time series shows a high degree of seasonality with concentration at its maximum in the winter (coincident with maximum discharge). The transport record is shown in figure 11B. The average is 19.4 tons per day and the standard deviation is 73.8 tons per day. The transport data also shows a downward trend($p = 0.015$) with a slope estimate of -0.071 tons per day per year or 0.4 percent of the mean per year. The relationship between flow and total phosphorus concentration is shown in figure 3A. The relationship is a strong one ($R^2 = 0.84$) and the slope is positive. The downtrends in concentration and transport could therefore be an artifact of the pattern of discharges observed. In fact, all of the five highest flows observed occurred in the first 3 years of the 8-year record. The time series of flow-adjusted concentrations are shown in figure 11C. The average *FAC* is 0.0 mg/L (by design) and the standard deviation is 0.07 mg/L.

The analysis does not indicate any trend in the *FAC* data ($p = 0.434$), the slope is estimated at only -0.002 mg/L per year or 1.6 percent of the mean concentration per year. This suggests that the trends in concentration and transport were indeed artifacts of the

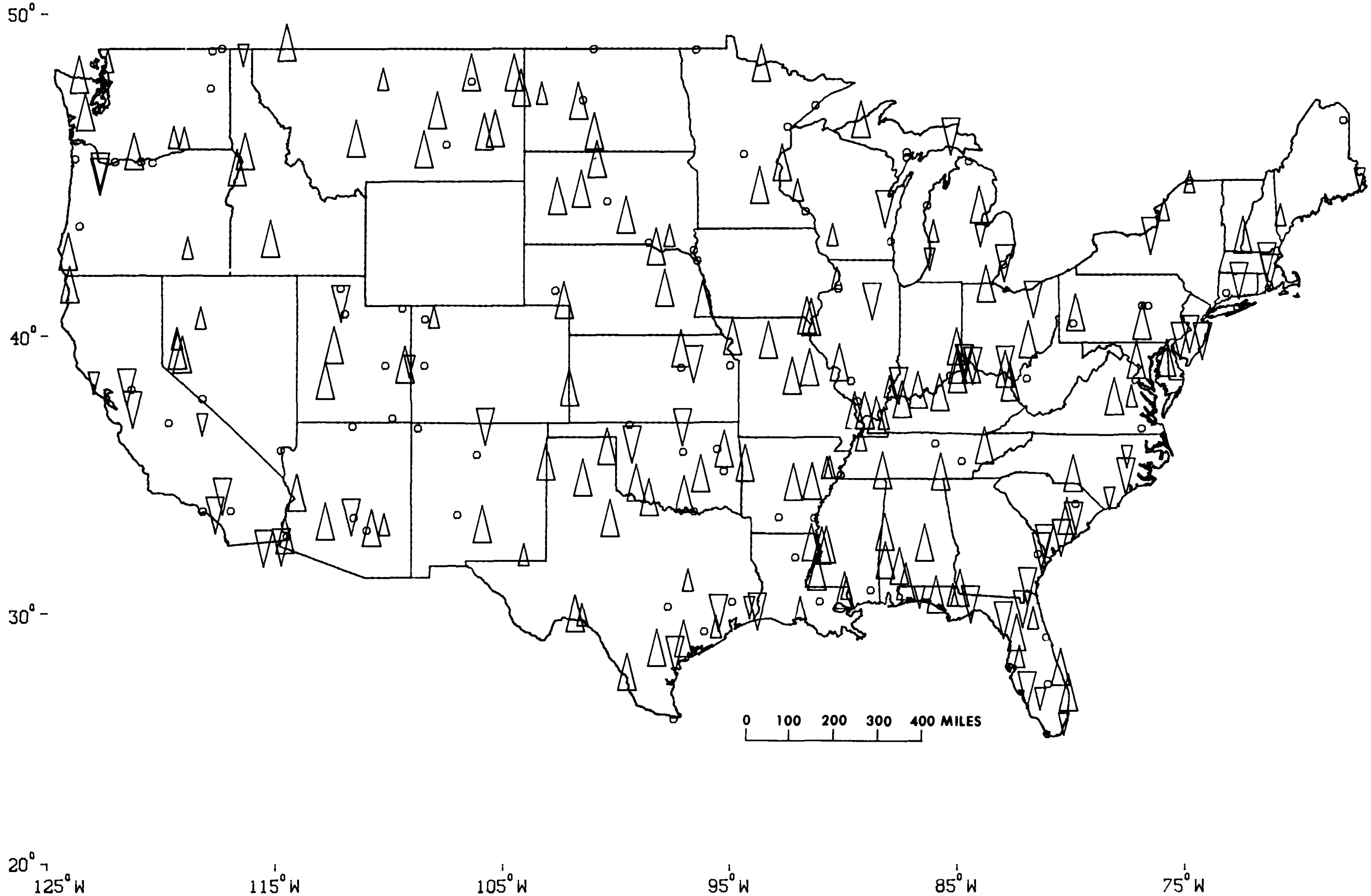

Figure 6. Slope of flow-concentration relationship for total phosphorus. Upwards pointing triangles indicate positive correlation and downwards pointing triangles indicate negative correlation. Small triangles show significant relationship ($p<0.1$); large triangles show highly significant relationship ($p<0.01$). Circles show stations with nonsignificant relationship.

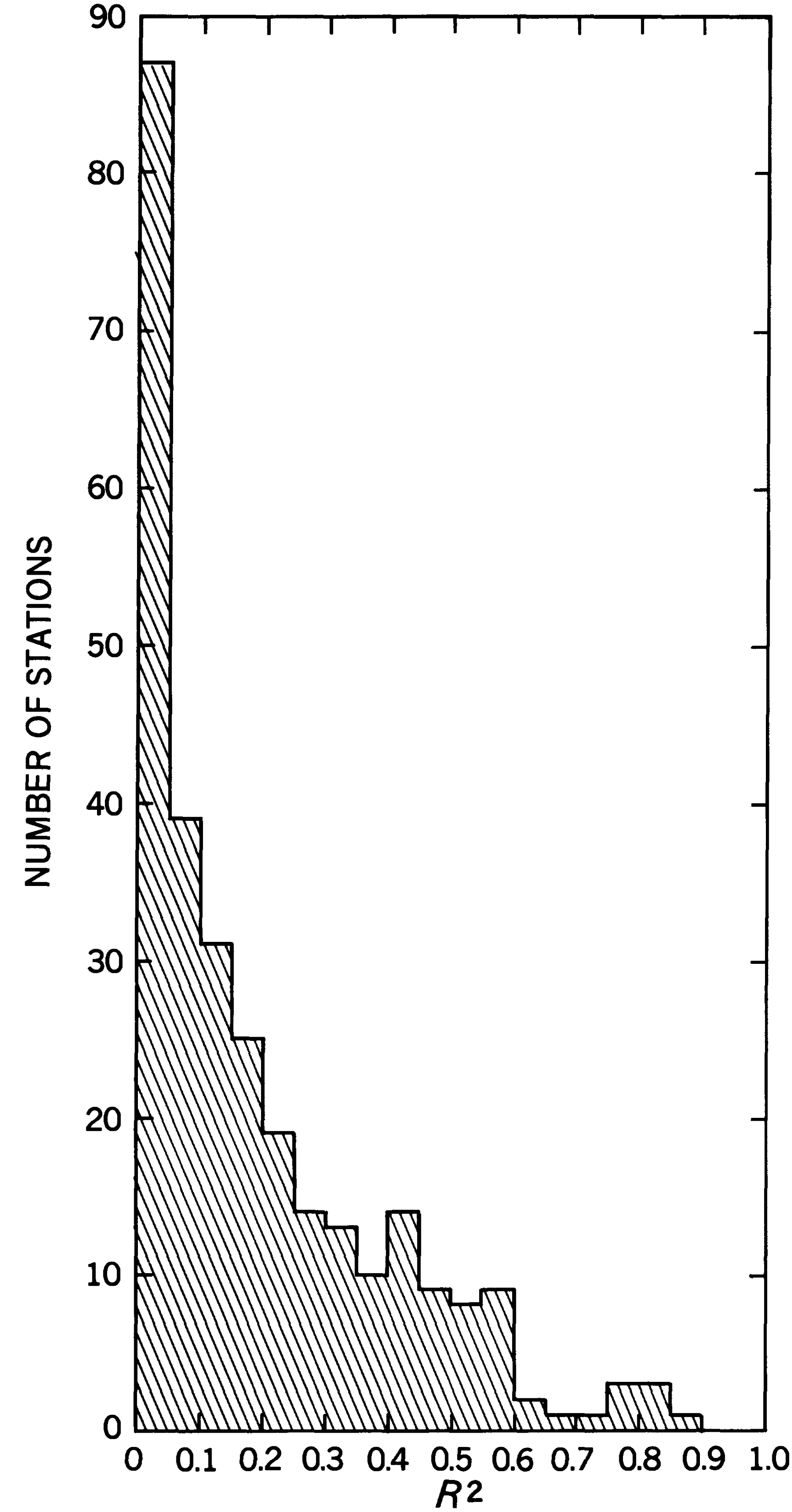

Figure 7. Results of regressions of total phosphorus concentration against discharge.

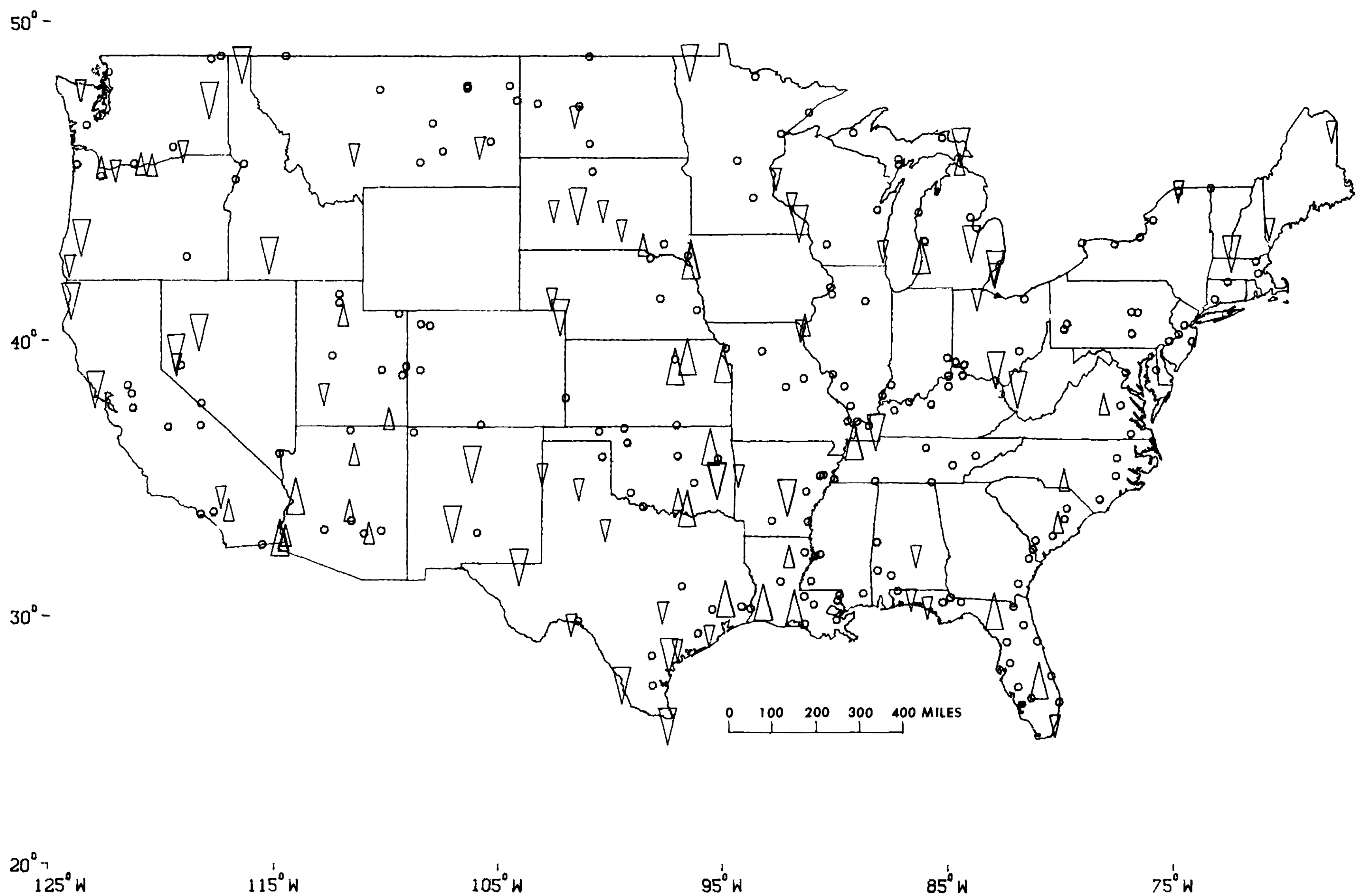

Figure 8. Results of tests for trends in total phosphorus concentration. Triangles point in direction of trend. Small symbols show significant trends ($p<0.1$); large symbols show highly significant ($p<0.01$) trends. Circles show stations with no significant trend.

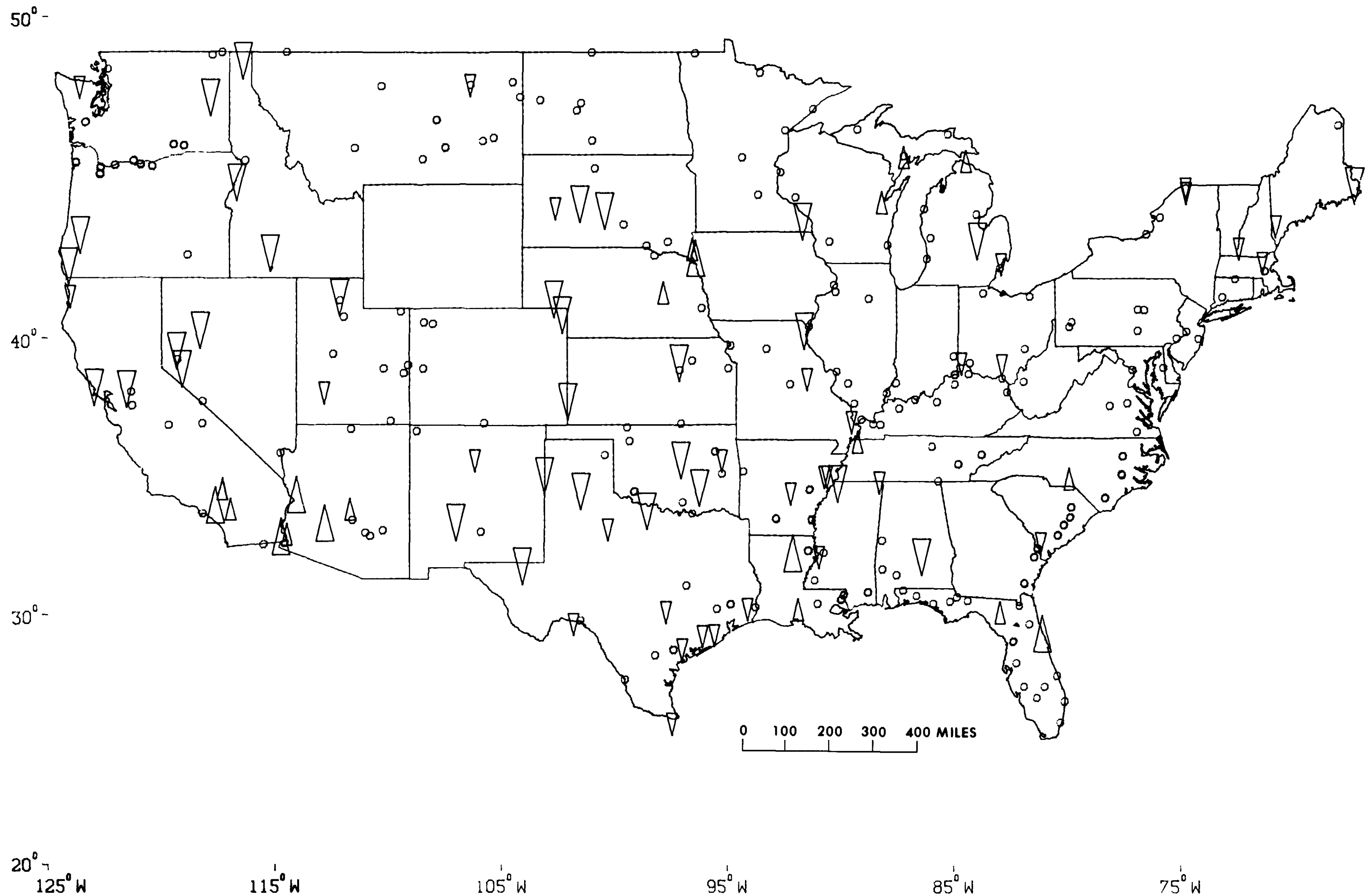

Figure 9. Results of tests for trends in total phosphorus transport. Triangles point in direction of trend. Small symbols show significant trends ($p<0.1$); large symbols show highly significant ($p<0.01$) trends. Circles show stations with no significant trend.

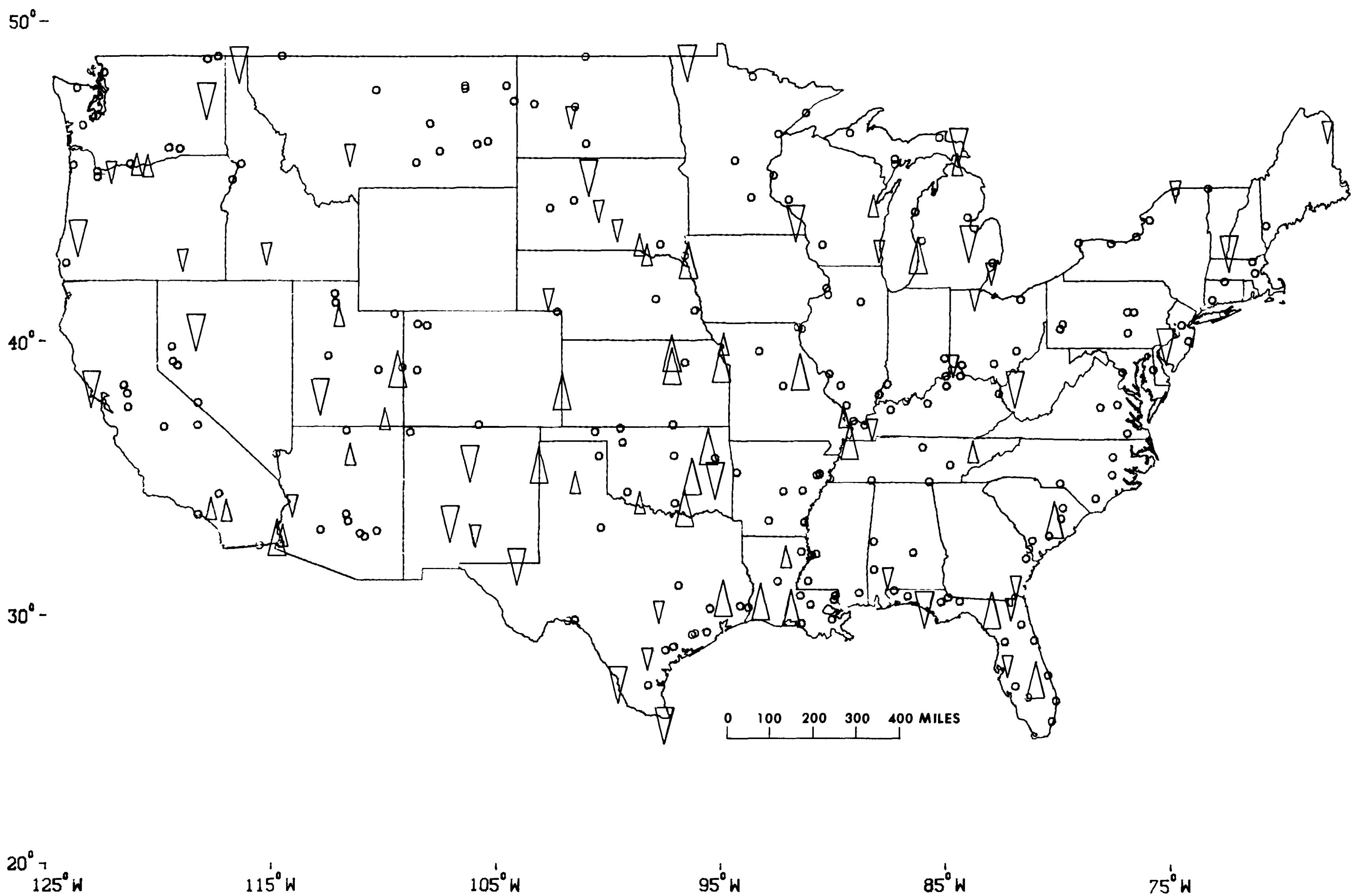

Figure 10. Results of tests for trends in flow-adjusted concentration of total phosphorus. Triangles point in direction of trend. Small symbols show significant trends ($p<0.1$); large symbols show highly significant ($p<0.01$) trends. Circles show stations with no significant trend.

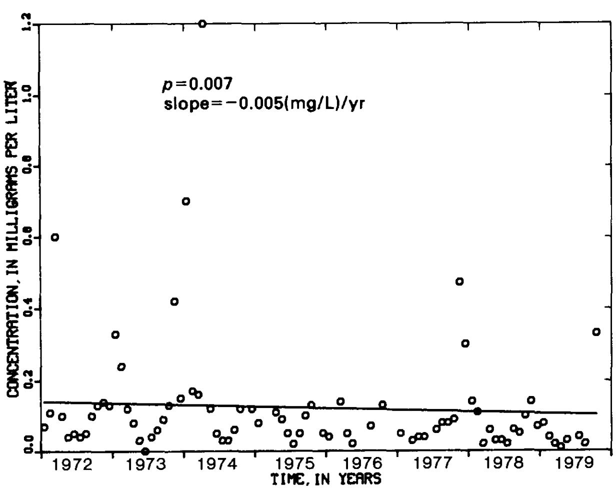

Figure 11A. Concentration of total phosphorus, Klamath River near Klamath, California.

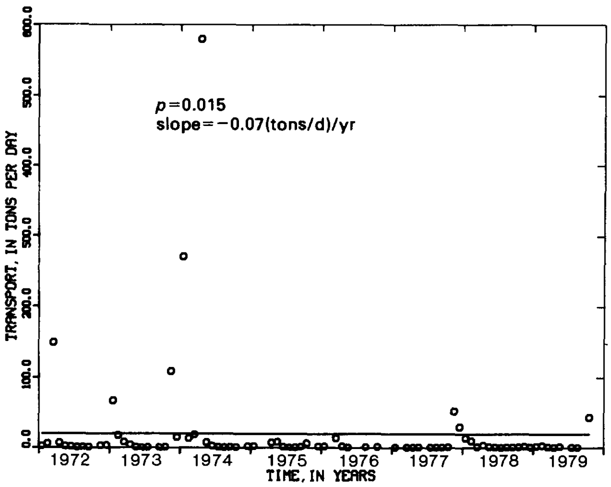

Figure 11B. Total phosphorus transport, Klamath River near Klamath, California.

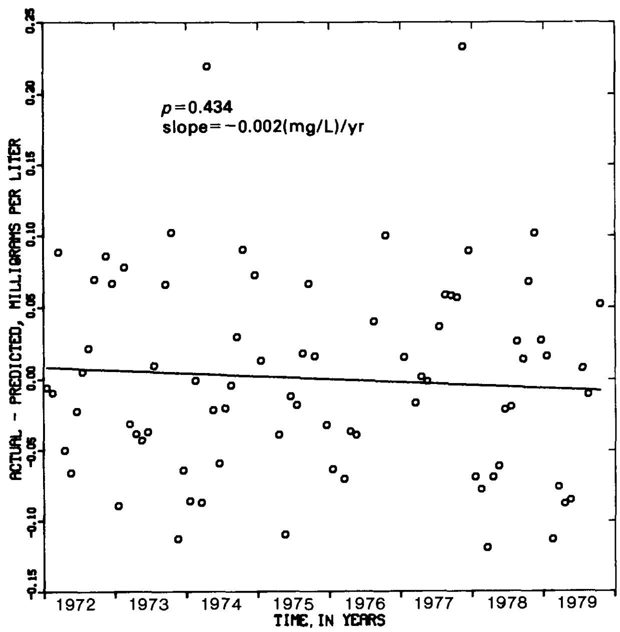

Figure 11C. Flow-adjusted concentration, Klamath River near Klamath, California.

Table 2. Trend test results using $\alpha=0.10$ to indicate trend for total phosphorus at NASQAN stations

	Downwards trend	No trend	Upwards trend	Number tested
Number of stations				
Concentration	62	203	38	303
Transport	62	204	23	289
Flow-adjusted concentration	45	218	40	303
Percent of stations				
Concentration	20.5	67.0	12.5	
Transport	21.5	70.6	8.0	
Flow-adjusted concentration	14.9	72.0	13.2	
Distribution under the null hypothesis (no trend)	5.0	90.0	5.0	

Table 3. Trend test results considering $\alpha=0.01$ to indicate trend for total phosphorus at NASQAN stations

	Downwards trend	No trend	Upwards trend	Number tested
Number of stations				
Concentration	27	261	15	303
Transport	31	251	7	289
Flow-adjusted concentration	22	261	20	303
Percent of stations				
Concentration	8.9	86.1	5.0	
Transport	10.7	86.9	2.4	
Flow-adjusted concentration	7.3	86.1	6.6	
Distribution under the null hypothesis (no trend)	.5	99.0	.5	

particular sequence of flows observed and that there is no evidence for any change in the processes contributing phosphorus to the river.

Consider another example, the Republican River at Clay Center, Kansas (station number 6856600, drainage area 24,542 square miles). The record of total phosphorus concentration is shown in figure 12A. The average concentration is 0.39 mg/L and the standard deviation is 0.24 mg/L. The analysis does not indicate the existence of a trend ($p=0.590$) and the slope estimate is only -0.006 mg/L per year or -1.5 percent of the mean per year. The transport record is shown in figure 12B. The average transport rate is 1.16 tons per day and the standard deviation is 2.35 tons per day. There is a highly significant trend in transport ($p=0.007$). The slope estimate is -0.054 tons per day per year or -4.7 percent of the mean per year. Examining the discharge record suggests that this apparent trend may be a consequence of a preponderance of high discharges in the first 1½ years of the 7 year record. The relationship between discharge and concentration is shown in figure 12C. The relationship is a positive one and this means that the effect of these higher flows would be more pronounced in the transport record than in the concentration record. The *FAC* record is shown in figure 12D. Its average is zero and standard deviation is 0.18 mg/L. The *FAC* data shows a highly significant ($p=0.005$) upward trend with an estimated slope of 0.022 mg/L per year or 5.6 percent of the mean concentration per year. This suggests that some change has taken place, resulting in greater inputs of phosphorus to the river, but that flow conditions over the record have masked the effect of this change.

These two examples show some of the possible types of results that arise. In any given case, the insights on stream quality are enhanced by considering all three trend analyses together. They will never reveal the cause of a change in stream quality, but they can lead to improved understanding of the kinds of causes to look for. Taken alone, they represent three diverse approaches to evaluating stream quality. Trends in concentration indicate what has happened over the period of record to the quality of water flowing in the river. Trends in transport indicate what changes have occurred in the flux of substances through the river system, suggesting what might be happening to the rates of output from various sources of phosphorus. Trends in *FAC* indicate that changes have occurred in the processes that deliver phosphorus to the river.

Nationwide Summary

Table 4 provides a comparison of the results of the tests for trend in concentration, transport, and *FAC*. It shows the number of stations at which any two of the three tests are in agreement and the numbers of each type of disagreement between them. For example, of 57 stations with downward trends in concentration, 1 had an upward trend in transport and 21 had no trend in transport.

Several geographic patterns emerge in the occurrence of significant trends in total phosphorus (figs. 8, 9, and 10). "Highly significant" increasing trends in concentration (fig. 8), for example, seem to occupy an identifiable region extending from the Midwest to the Southeast, including stations in Nebraska, Kansas, Oklahoma, Texas,

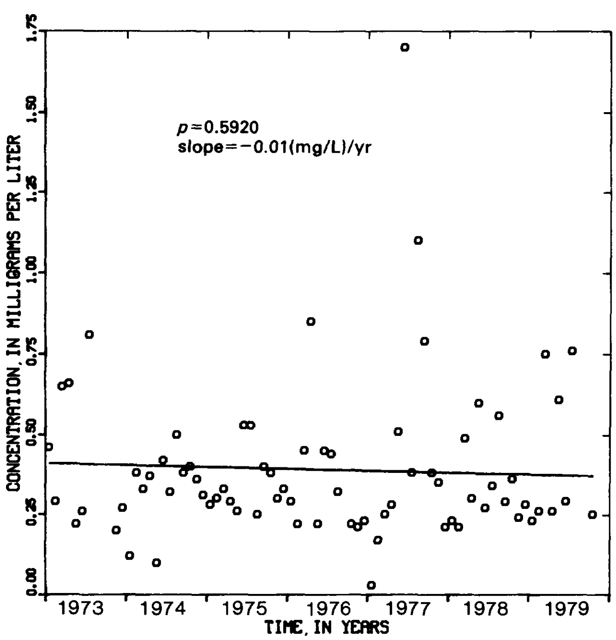

Figure 12A. Concentration of total phosphorus, Republican River at Clay Center, Kansas.

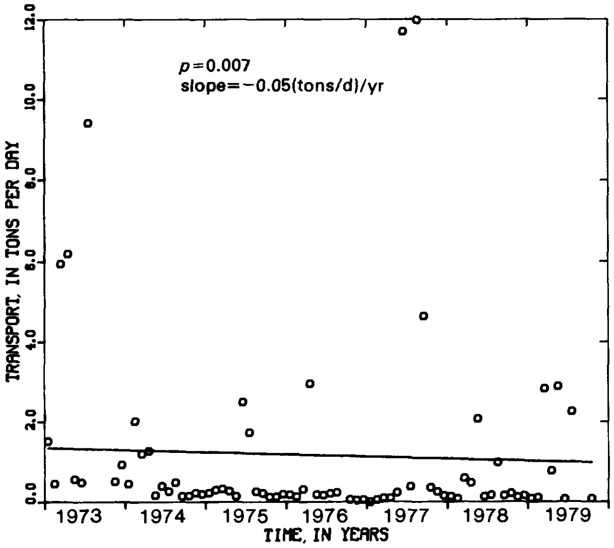

Figure 12B. Total phosphorus transport, Republican River at Clay Center, Kansas.

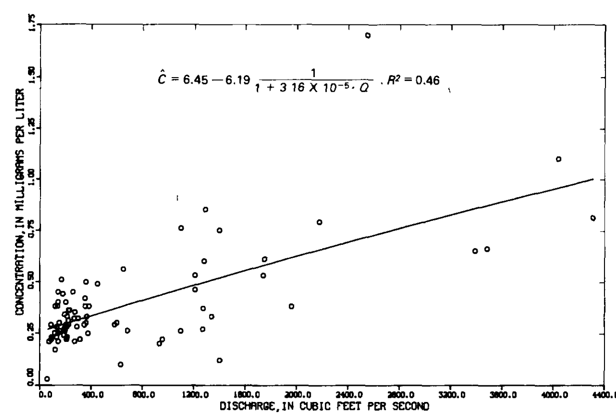

Figure 12C. Relationship between discharge and total phosphorus concentration, Republican River at Clay Center, Kansas.

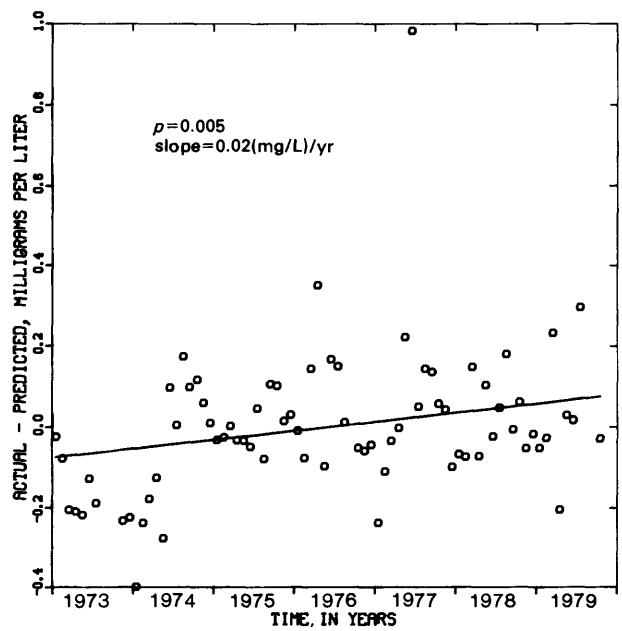

Figure 12D. Flow-adjusted concentration of total phosphorus, Republican River at Clay Center, Kansas.

Louisiana, and Florida. This same pattern becomes even more accentuated in the map of flow-adjusted trends in concentration (fig. 10), and expands to include stations in Colorado, Missouri, Michigan, Tennessee, and South Carolina, in addition to those named above. In contrast, a large majority of the "highly significant" downward trends in *FAC* occur outside the region described above, in States to the west, north, and northeast of those named.

Notwithstanding the pattern in trends in phosphorus concentration, trends in phosphorus transport are downward in the large majority of cases showing trend (30 out of a total 37 stations). The major regional exception to this pattern seems to be a group of stations in Arizona and southern California which show uptrends in phosphorus transport.

Explanations for the occurrence of trends and for observable geographic patterns in trends are not readily apparent and are outside the scope of this paper. A few points are worth making, however. In the case of many of the stations showing declining phosphorus transport rates, it seems likely that decreased streamflows which occurred widely in the latter 1970's would likely lead to downward trends in transport, especially in the West and Midwest. The effect of changing flows on transport rates is, of course, doubly important in cases where the dependence of concentration on flow is positive.

The question of what have been the causes of trends in flow-adjusted concentration is perhaps the most important one to pose, since the flow-adjustment procedure was undertaken here in an attempt to elucidate changes in the processes which deliver phosphorus to streams, whether these be related to population and land-use changes, pollution-abatement efforts, or more natural causes.

Table 4. Number of stations showing each of nine possible combinations of results from each pair of trend tests on total phosphorus data. The indicator of trend is taken as $\alpha=0.10$

	Transport			
	Upwards trend	*No trend*	*Downwards trend*	*Total*
Concentration:				
Upwards trend	15	21	0	36
No trend	7	160	25	192
Downwards trend	1	23	37	61
Total	23	204	62	289
	Flow-Adjusted Concentration (*FAC*)			
	Upwards trend	*No trend*	*Downwards trend*	*Total*
Concentration:				
Upwards trend	26	11	1	38
No trend	12	180	11	203
Downwards trend	2	27	33	62
Total	40	218	45	303
	Flow-Adjusted Concentration (*FAC*)			
	Upwards trend	*No trend*	*Downwards trend*	*Total*
Transport:				
Upwards trend	13	9	1	23
No trend	17	163	24	204
Downwards trend	8	35	19	62
Total	38	207	44	289

APPENDIX A: RESULTS BY STATION

For each of the 308 stations considered in the study, averages of discharge, phosphorus concentration, and phosphorus transport are given in table A. Also listed are the Seasonal Kendall Slope estimates for concentration, transport, and flow-adjusted concentration. The slope values are given in percentage terms for ease of comparison. That is: "trend %/yr" means the slope in mg/L (tons per day) per year divided by the average value in mg/L (tons per day) and multiplied by 100. The units in all cases are percent (of average) per year. Those slopes that are statistically significant at the 10 percent level are marked with an "*S*" and those at the 1 percent level by an "*HS*" corresponding to "significant" and "highly significant."

Also shown is the square of the correlation coefficient ("*r* squared") obtained in the most significant regression for flow adjustment. This is also marked "significant" (*S*) or "highly significant" (*HS*). A positive or negative slope of the fitted flow-adjustment equation (concentration versus discharge) is indicated by a plus (+) or minus (−), respectively.

Table A. Results by station—Continued
Total phosphorus

Station number	Station name	Mean discharge (cfs)	Concentration mean (mg/L)	Concentration trend (%/yr)	Transport mean (tons/day)	Transport trend (%/yr)	Flow-adjusted concentration trend (%/yr)	Flow-adjusted concentration regression r (squared)	regression (type)	regression (slope)
41657.00	DETROIT R AT DETROIT, MICH	217537	0.05	-0.0S	8.651	1.6	-0.0S	0.01	lin	-
41935.00	MAUMEE R AT WATERVILLE, OH	5902	0.29	-3.5S	8.039	-0.9	-4.5S	0.30HS	hyp	+
42080.00	CUYAHOGA R AT INDEPENDENCE, OH	994	0.42	-1.2	0.969	-5.9	0.9	0.47HS	inv	-
42196.40	NIAGARA R(L ONTARIO) AT FORT NIAGARA, NY	242062	0.03	-0.0	16.566	--	-0.0	--		
42320.06	GENESEE RIVER(CHARLOTTE DOCKS)AT ROCHESTER, NY	2288	0.14	-7.0	0.799	--	-7.0	--		
42490.00	OSWEGO RIVER AT LOCK 7 AT OSWEGO, NY	8279	0.08	-4.0	1.712	-4.4	-4.1	0.24HS	hyp	-
42605.00	BLACK RIVER AT WATERTOWN, NY	4963	0.03	0.0	0.477	-1.7	0.8	0.03S	lin	+
42643.31	ST LAWRENCE R AT CORNWALL ONT NR MASSENA, NY	282742	0.05	-0.0S	17.844	-9.1S	-0.0S	0.01	lin	-
42690.00	ST REGIS RIVER AT BRASHER CENTER, NY	1175	0.02	-0.0	0.074	-10.4S	-12.2	0.06S	hyp	+
42950.00	RICHELIEU R (L CHAMPLAIN) AT ROUSES POINT, NY	--	0.02	-0.0	--	--	-0.0	--		
51120.00	ROSEAU RIVER BELOW STATE DITCH 51 NR CARIBOU, MN	327	0.14	-7.2HS	0.168	-0.4	-7.2HS	0.01	lin	+
51240.00	SOURIS RIVER NR WESTHOPE, ND	683	0.34	-1.1	0.420	-0.2	-1.1	0.01	hyp	-
51315.00	LITTLE FORK RIVER AT LITTLEFORK, MN	1319	0.05	-0.0	0.349	-0.1	-1.8	0.53HS	hyp	+
52670.00	MISSISSIPPI RIVER NEAR ROYALTON, MN	5328	0.05	-0.0	0.838	3.3	-0.0	0.01	hyp	+
53300.00	MINNESOTA RIVER NEAR JORDAN, MN	3331	0.26	-1.9	2.844	-0.4	-2.8	0.22HS	hyp	+
53405.00	ST. CROIX RIVER AT ST. CROIX FALLS, WI	5236	0.04	-0.0	0.709	-0.1	-4.3	0.32HS	hyp	+
53695.00	CHIPPEWA RIVER AT DURAND, WI	7566	0.11	-3.1S	2.350	0.7	-2.7	0.05S	hyp	+
53785.00	MISSISSIPPI RIVER AT WINONA, MN	28137	0.16	-6.3HS	12.540	-6.8HS	-6.3HS	0.01	hyp	+
54070.00	WISCONSIN RIVER AT MUSCODA, WI	8654	0.08	-0.0	1.990	1.8	-2.1	0.06S	lin	+
54205.00	MISSISSIPPI RIVER AT CLINTON, IOWA	48637	0.18	0.0	25.408	5.5	-1.6	0.06S	hyp	+
54465.00	ROCK RIVER NEAR JOSLIN, IL	6700	0.36	-1.4	6.786	-0.9	-1.4	0.01	hyp	+
54745.00	MISSISSIPPI RIVER AT KEOKUK, IOWA	72832	0.24	4.2S	51.353	4.0	5.7	0.15HS	hyp	+
54906.00	DES MOINES RIVER AT ST. FRANCISVILLE, MO	9895	0.26	-3.9S	8.092	-10.3HS	2.4	0.13HS	log	+
55435.00	ILLINOIS RIVER AT MARSEILLES, IL	8815	0.62	-4.1	13.034	-6.4	-3.5	0.14HS	inv	-
55875.50	MISSISSIPPI RIVER BELOW ALTON, IL	107243	0.27	-0.0	100.576	-3.5	1.6	0.31HS	hyp	+
55941.00	KASKASKIA RIVER NEAR VENEDY STATION, IL	3527	0.21	-6.3	2.243	1.1	-6.3	0.00	lin	+
55995.00	BIG MUDDY RIVER AT MURPHYSBORO, IL	1774	0.23	0.6	1.009	-5.4	0.6	0.03	inv	-
60545.00	MISSOURI RIVER AT TOSTON, MT	5611	0.06	-5.3S	1.374	-2.5	-5.3S	0.46HS	hyp	+
61095.00	MISSOURI RIVER AT VIRGELLE, MT	10612	0.13	-2.3	5.107	-1.0	5.1	0.10S	hyp	+
61305.00	MUSSELSHELL RIVER AT MOSBY, MT	725	0.19	-0.0	2.079	0.0	-4.5	0.77HS	lin	+
61320.00	MISSOURI RIVER BELOW FORT PECK DAM, MT	11986	0.02	0.0	0.544	0.4	0.0	0.01	hyp	-
61745.00	MILK RIVER AT NASHUA, MT	1397	0.23	-4.3	2.191	-0.4S	-6.3	0.54HS	hyp	+
61855.00	MISSOURI RIVER NEAR CULBERTSON, MT	13470	0.12	-2.1	5.689	-0.6	-3.7	0.21HS	hyp	+
62145.00	YELLOWSTONE RIVER AT BILLINGS, MT	7447	0.06	-6.5	2.202	-3.4	-7.1	0.23HS	hyp	+
62947.00	BIGHORN RIVER AT BIGHORN, MT	4434	0.07	-4.1	0.984	-2.8	-4.1	0.04	hyp	+
63085.00	TONGUE RIVER AT MILES CITY, MT	665	0.16	-2.6	0.912	-0.1	-2.1	0.54HS	lin	+
63265.00	POWDER RIVER NEAR LOCATE, MT	933	0.76	-0.0	4.277	-0.3	3.8	0.35HS	hyp	+
63295.00	YELLOWSTONE RIVER NEAR SIDNEY, MT	13835	0.20	-1.7	11.713	-1.3	1.0	0.34HS	hyp	+
63370.00	LITTLE MISSOURI RIVER NR WATFORD CITY, ND	589	1.33	0.5	4.020	0.1	-3.7	0.11S	hyp	+
63384.90	MISSOURI RIVER AT GARRISON DAM, ND	30945	0.02	-0.0	1.293	-20.5	-0.0	0.02	hyp	+
63405.00	KNIFE RIVER AT HAZEN, ND	119	0.11	-4.6S	0.113	0.1	-5.3S	0.58HS	hyp	+
63540.00	CANNONBALL RIVER AT BREIEN, ND	393	0.15	0.0	0.716	0.0	-3.1	0.78HS	hyp	+
63578.00	GRAND R AT LITTLE EAGLE, SD	663	0.23	-4.4	1.743	-0.0	-7.7HS	0.36HS	hyp	+
64380.00	BELLE FOURCHE R NEAR ELM SPRINGS, SD	492	0.38	-1.3S	2.270	-0.0S	-0.4	0.85HS	hyp	+
64393.00	CHEYENNE R AT CHERRY CREEK, SD	789	0.61	-7.0HS	2.820	-0.8HS	-1.8	0.15HS	hyp	+
64400.00	MISSOURI R AT PIERRE, SD	38922	0.04	-5.7S	3.465	-6.1HS	-5.7S	0.00	lin	-
64520.00	WHITE R NEAR OACOMA, SD	500	4.66	-3.2S	8.632	-0.0	-19.0S	0.20HS	hyp	+
64530.00	MISSOURI R AT FORT RANDALL, SD	35134	0.05	4.1S	3.458	3.1	4.1S	0.03	hyp	-
64655.00	NIOBRARA RIVER NR. VERDEL, NEBR	1483	0.29	1.7	1.398	0.7	3.2S	0.25HS	hyp	+
64785.00	JAMES R NEAR SCOTLAND, SD	425	0.37	0.7	0.544	-0.4	-0.4	0.06S	hyp	+

Table A. Results by station—Continued
Total phosphorus

Station number	Station name	Mean discharge (cfs)	Concentration mean (mg/L)	Concentration trend (%/yr)	Transport mean (tons/day)	Transport trend (%/yr)	Flow-adjusted concentration trend (%/yr)	Flow-adjusted concentration regression r (squared)	Flow-adjusted concentration regression (type)	Flow-adjusted concentration regression (slope)
64855.00	BIG SIOUX R AT AKRON, IA	902	1.47	0.8	2.917	2.5S	0.8	0.00	inv	-
64860.00	MISSOURI RIVER AT SIOUX CITY, IOWA	34558	0.07	9.5HS	7.077	17.5HS	9.5HS	0.04	hyp	+
66860.00	NORTH PLATTE RIVER AT LISCO, NEBR	1379	0.23	-4.4S	0.760	-12.5HS	-4.4S	0.02	hyp	-
67640.00	SOUTH PLATTE RIVER AT JULESBURG, CO	551	0.25	-12.1HS	0.750	-3.5HS	-2.7	0.52HS	hyp	+
67924.99	LOUP R POWER CA AT DIV NR GENOA, NEBR	1751	0.31	0.0	1.572	5.6S	-1.4	0.18HS	lin	+
68055.00	PLATTE R AT LOUISVILLE, NE	5813	0.57	1.8	17.845	1.0	0.4	0.68HS	lin	+
68180.00	MISSOURI RIVER AT ST. JOSEPH, MO	48970	0.38	-1.3	61.338	-2.5	7.6S	0.25HS	lin	+
68566.00	REPUBLICAN R AT CLAY CENTER, KS	721	0.39	-1.5	1.160	-4.7HS	5.7HS	0.46HS	hyp	+
68776.00	SMOKY HILL R AT ENTERPRISE, KS	2011	0.29	9.3HS	1.404	-0.7	9.3HS	0.03	hyp	+
68870.00	BIG BLUE R NR MANHATTAN, KS	2466	0.40	3.6HS	1.518	0.6	4.6	0.09HS	hyp	-
68923.50	KANSAS R AT DESOTO, KS	9948	0.37	10.7HS	8.421	-1.1	10.7HS	0.02	lin	-
69020.00	GRAND RIVER NEAR SUMNER, MO	5410	0.38	-1.7	12.592	-0.2	1.0	0.53HS	hyp	+
69265.10	OSAGE RIVER BELOW ST. THOMAS, MISSOURI	8201	0.05	-4.7	1.583	-17.9	5.5	0.27HS	hyp	+
69345.00	MISSOURI RIVER AT HERMANN, MO	88375	0.33	-0.8	102.534	-3.7S	10.8HS	0.18HS	hyp	+
70220.00	MISSISSIPPI RIVER AT THEBES, ILL	227142	0.32	0.0	232.842	-8.5S	6.9S	0.32HS	hyp	+
70260.00	OBION RIVER AT OBION, TENN	2730	0.33	11.0HS	3.112	4.8S	11.8HS	0.11S	inv	+
70320.00	MISSISSIPPI RIVER AT MEMPHIS, TENN	470153	0.25	-4.1	304.263	-15.0HS	-4.1	0.03	inv	+
70478.00	ST. FRANCIS RIVER AT PARKIN, ARK	2599	0.44	1.1	3.725	-14.3S	3.7	0.12S	log	+
70479.00	ST. FRANCIS BAY AT RIVERFRONT, ARK	7619	0.25	-3.9	6.299	-13.0S	-0.5	0.15S	hyp	+
70778.00	WHITE RIVER AT CLARENDON, ARK	25838	0.09	-0.0	7.618	-7.8	4.3	0.14HS	lin	+
71375.00	ARKANSAS RIVER NEAR COOLIDGE, KANS	54	0.46	-1.1	0.207	-0.3HS	24.6HS	0.26HS	hyp	+
71465.00	ARKANSAS R AT ARKANSAS CITY, KS	1947	0.94	2.7	3.618	0.3	2.4	0.08HS	inv	-
71579.50	CIMARRON RIVER NR BUFFALO, OK	149	0.34	3.0	0.227	-0.0	3.0	0.06	hyp	+
71610.00	CIMARRON RIVER AT PERKINS, OK	2813	0.58	2.1	4.496	-6.2HS	2.1	0.02	hyp	+
71786.20	NEWT GRAHAM LOCK AND DAM NR INOLA, OK	6515	0.30	13.1HS	2.921	-43.8	13.1HS	0.07	hyp	-
71935.00	NEOSHO RIVER BLW FT GIBSON LAKE NR FT GIBSON, OK	12878	0.08	-4.3	3.196	-11.2S	-0.4	0.17HS	hyp	+
72271.40	CANADIAN RIVER ABOVE NM-TX STATE LINE, NM	88	0.81	-1.1S	1.611	-0.0HS	17.3HS	0.22HS	log	+
72280.00	CANADIAN R NR CANADIAN, TX	182	0.15	0.0	0.187	0.0	4.5	0.20HS	hyp	+
72315.00	CANADIAN RIVER AT CALVIN, OK	1668	0.34	6.3	3.130	-1.2HS	9.9HS	0.41HS	lin	+
72340.00	BEAVER RIVER AT BEAVER, OK	17	0.15	-0.7	0.032	--	-0.7	--		
72375.00	NORTH CANADIAN RIVER AT WOODWARD, OK	105	0.79	-3.8	0.085	6.1	-4.7	0.58HS	hyp	-
72450.00	CANADIAN RIVER NR WHITEFIELD, OK	4826	0.10	-6.4HS	2.242	-2.8	-6.4HS	0.01	hyp	+
72505.50	ARKANSAS R. AT DAM NO. 13, NR VAN BUREN, AR	40149	0.14	-4.6S	23.039	-0.9	-0.7	0.24HS	lin	+
72636.20	ARKANSAS R @ DAVID D TERRY L&D BL LITTLE ROCK, AR	47142	0.13	-5.2HS	23.400	-3.3S	1.0	0.21HS	lin	+
72654.50	MISSISSIPPI RIV NR ARKANSAS CITY, ARK	564590	0.22	0.0	337.321	-2.9	0.0	0.01	lin	-
72890.00	MISSISSIPPI RIVER AT VICKSBURG, MS	767281	0.23	0.0	518.873	-17.7S	6.3	0.24HS	inv	+
72900.00	BIG BLACK RIVER NR BOVINA, MS	4931	0.29	-3.4	4.612	-1.4	-2.7	0.23HS	hyp	+
72925.00	HOMOCHITTO RIVER AT ROSETTA, MS	899	0.06	0.0	0.192	-1.3	17.0	0.23HS	lin	+
72979.10	PDTF RED RIVER NEAR WAYSIDE, TEX	11	0.20	-1.6	0.044	-0.1HS	4.7S	0.61HS	hyp	+
73050.00	NORTH FORK RED RIVER NR HEADRICK, OK	238	0.14	-0.0	0.191	-1.0	15.1	0.57HS	hyp	+
73085.00	RED RIVER NR BURKBURNETT, TX	1250	0.24	-5.2	2.068	-2.1HS	7.3S	0.49HS	hyp	+
73310.00	WASHITA RIVER NR DURWOOD, OK	1003	0.28	6.3S	1.131	-1.2	6.8	0.32HS	hyp	+
73316.00	RED RIVER AT DENISON DAM NR DENISON, TX	5831	0.06	8.9HS	0.824	-5.9	8.9HS	0.05	hyp	+
73555.00	RED R AT ALEXANDRIA	--	0.21	2.4	--	--	2.4	--		
73620.00	OUACHITA RIVER AT CAMDEN, ARK	5054	0.06	0.0	0.867	-6.8	0.0	0.02	hyp	+
73676.40	OUACHITA RIVER AT COLUMBIA, LA	17174	0.08	5.9S	4.047	26.3HS	5.9S	0.00	hyp	+
73695.00	TENSAS RIVER AT TENDAL, LOUISIANA	441	0.31	1.6	0.520	-0.3	0.1	0.43HS	hyp	+
73734.20	MISSISSIPPI RIVER NEAR ST. FRANCISVILLE, LA	--	0.22	6.1	--	--	6.1	--		
73745.25	MISSISSIPPI RIVER AT BELLE CHASSE, LA	608406	0.26	2.2	384.859	--	2.2	--		
73785.10	AMITE R AT 4H CAMP NR DENHAM SPRINGS	2928	0.12	0.0	1.224	-0.2	0.0	0.02	lin	+

Table A. Results by station—Continued
Total phosphorus

Station number	Station name	Mean discharge (*cfs*)	Concentration mean (mg/L)	Concentration trend (%/yr)	Transport mean (tons/day)	Transport trend (%/yr)	Flow-adjusted concentration trend (%/yr)	Flow-adjusted concentration regression (r squared)	Flow-adjusted concentration regression (type)	Flow-adjusted concentration regression (slope)
162130.00	WAIKELE STREAM AT WAIPAHU, OAHU, HI	30	1.57	6.4S	0.080	3.0	4.3	0.26HS	hyp	-
162293.00	KALIHI STREAM AT KALIHI, OAHU, HI	8	0.11	-4.6	0.004	-1.5	-4.6	0.02	log	+
164000.00	HALAWA STREAM NR HALAWA, MOLOKAI, HI	42	0.05	6.6S	0.021	0.9S	8.4S	0.51HS	lin	+
166180.00	KAHAKULOA STREAM NR HONOKOHAU, MAUI, HI	14	0.02	-0.0	0.001	3.6	-0.9	0.15HS	lin	+
500381.00	RIO GRANDE DE MANATI AT HWY 2 NR MANATI, PR	276	0.17	5.8S	0.173	4.9S	6.2	0.27HS	lin	+
500460.00	RIO DE LA PLATA AT TOA ALTA, PR	120	0.13	7.7S	0.044	6.0S	7.7S	0.01	inv	+
500920.00	RIO GRANDE DE PATILLAS NR PATILLAS	54	0.04	-0.0	0.010	-0.8	-19.7HS	0.11HS	hyp	+
501440.00	RIO GRANDE DE ANASCO NR SAN SEBASTIAN, PR	200	0.09	-5.8	0.059	-3.3	-4.2	0.14HS	hyp	+

APPENDIX B: THE SEASONAL KENDALL PROCEDURES

Kendall's Tau

For a time series $x_1, ***, x_n$, consider each difference $d_{ij} = x_i - x_j$ where $1 \leq j < i \leq n$. There are $\binom{n}{2} = n(n-1)/2$ such differences. Let P be the number of positive differences and Q be the number of negative differences. Then Kendall's τ (tau) is defined (Kendall, 1975) as:

$$\tau = \frac{P-Q}{n(n-1)/2}$$

If all the differences (d_{ij}) are positive, $\tau = 1$. If all the differences are negative, $\tau = -1$. If the differences are equally divided between pluses and minuses, $\tau = 0$.

In essence, τ measures the correlation between the series of x_i's and time. If the series is independently distributed in time, the expected value of τ is 0 and the variance of $S = P - Q$ is $n(n-1)(2n+5)/18$. The exact (discrete) distribution of τ is fairly easy to calculate for small n. For large n, the ratio $z = S/\sqrt{n(n-1)(2n+5)/18}$ has approximately the standard normal distribution. Corrections for ties ($d_{ij} = 0$) and for continuity are discussed in Kendall (1975).

Seasonal Kendall test

The test for trend used in this study is a modification of Kendall's Tau. In the Seasonal Kendall test, the only differences considered are those between observations occurring in the same month of the year. Assume there are n years of monthly observations with x_{ij} being the (possibly missing) observation for the ith month ($i = 1,2,***,12$) of the jth year ($j = 1,2,***,n$). For each month, the number of nonmissing values is n_i. Note that $n_i \leq n$. The number of valid comparisons for each month is $m_i = n_i(n_i - 1)/2$. For each month i, compute all of the valid differences, $x_{ij} - x_{ik}$ for $1 \leq k < j \leq n$. The number of positive differences is P_i and the number of negative differences is Q_i. Note that $P_i + Q_i \leq n_i < n$. The sum $P_i + Q_i$ will be less than n_i only when there are ties. The score (S_i) for the month is $S_i = P_i - Q_i$ and, under the null hypothesis, the expectation of S_i is 0 and the variance of the score is $v_i = n_i(n_i - 1)(2n_i + 5)/18$. For each tie of k values, v_i is reduced by $k(k-1)(2k+5)/18$. Combining the 12 months, the number of valid comparisons is $m = \sum_{i=1}^{12} m_i$, the total score is $S = \sum_{i=1}^{12} S_i$ and the total variance (under the null hypothesis) is $v = \sum_{i=1}^{12} v_i$ (note that the covariances of the S_i's are zero). Now the desired statistic is $\tau = S/m$. Due to the fact that S may take on only values two units apart, a continuity correction (Kendall, 1975) is necessary for computing Z, the standard normal deviate.

$$Z = \begin{cases} \dfrac{S-1}{\sqrt{v}} & \text{for } S = 1,2,*** \\ 0 & \text{for } S = 0 \\ \dfrac{S+1}{\sqrt{v}} & \text{for } S = -1,-2,*** \end{cases}$$

Seasonal Kendall Slope Estimator

The Seasonal Kendall Slope Estimator (denoted B) is defined as the median of all d_{ijk} values for all $i = 1,2,***,12$ and $1 \leq k < j \leq n$ where:

$$d_{ijk} = \frac{x_{ij} - x_{ik}}{j-k}$$

Because it is based on the same set of differences as the Seasonal Kendall test, they may be computed concurrently. The slope estimator B has the property that if a time series y_{ij} ($i = 1,2,***,12$, $j = 1,2,***,n$) is computed by:

$$y_{ij} = x_{ij} - B\left(\frac{i}{12} + j\right)$$

Then, the slope estimate for this y_{ij} series will be exactly zero. Furthermore, if there is no more than one zero difference $y_{ij} - y_{ik}$, the Seasonal Kendall test will show the y_{ij} series to be trend free in the sense that $P_i = Q_i$. This can be seen as follows:

1. Let $d_{ijk} = (x_{ij} - x_{ik})/(j-k)$ $i = 1,***,12$; $1 \leq k < j \leq n$.
2. Let B = median of d_{ijk}.
3. Set $y_{ij} = x_{ij} - B(j + i/12)$.
4. Set $e_{ijk} = (y_{ij} - y_{ik})/(j-k)$ $i = 1,***,12$; $1 \leq k < j \leq n$:
5. Then
$$e_{ijk} = \frac{y_{ij} - y_{ik}}{j-k} = \frac{x_{ij} - B(j+i/12) - x_{ik} + B(k+i/12)}{j-k} = \frac{x_{ij} - x_{ik}}{j-k} - B\frac{(j+i/12)-(k+i/12)}{j-k} = d_{ijk} - B$$
6. So that
$$B' = \text{median of } \{e_{ijk}\} = \text{median of } \{d_{ijk}\} - B = \text{median of } \{d_{ijk}\} - B = B - B = 0.$$

A Fortran subroutine to perform the Seasonal Kendall procedures is shown in figure B-1.

```
      SUBROUTINE SEAKEN(X,N,TAU,ALPHA,SLOPE)
C         MODIFIED KENDALL'S TAU TEST FOR TREND IN MONTHLY DATA.
C         VECTOR X SHOULD CONTAIN THE N MONTHS OF DATA.
C         ALL MISSING VALUES SHOULD BE -999999.0.
C         TAU IS THE RESULTANT STATISTIC EQUIVALENT TO KENDALL'S TAU.
C         ALPHA IS THE SIGNIFICANCE LEVEL OF TAU.
C         SLOPE IS THE ESTIMATE OF THE SLOPE OF THE TREND.
      REAL X(N), Y(5000)
      LOGICAL ODD
      LOGICAL WASTIE(5000)
      REAL XMIS/-999998.0/
C         CHECK FOR ENOUGH WORK STORAGE IN ARRAY Y TO HOLD THE DIFFERENCES.
      M = 6 * ((N/12) + 1) * (N/12)
      IF (M.GT.5000) PRINT, 'IN SUBROUTINE SEAKEN, THE DIMENSION OF ',
     &   'THE ARRAY Y MUST BE INCREASED TO ', M, ' FROM 5000.'
      IF (M.GT.5000) STOP
C        CHECK WASTIE
      IF (N.GT.5000) PRINT, "IN SUBROUTINE SEAKEN, THE DIMENSION OF",
     &   " THE ARRAY WASTIE MUST BE INCREASED TO ", N," FROM 5000."
      IF (N.GT.5000) STOP
C         ZERO OUT THE COUNTERS.
      DO 100 I=1,N
      WASTIE(I)=.FALSE.
  100 CONTINUE
      NPLUS = 0
      NMINUS = 0
      NCOMPT = 0
      VARTOT = 0.0
      INDEX = 0
      FIXVAR=0.0
C         DO EACH MONTH.
      DO 10 MONTH = 1,12
      NCOMP = 0
C         PICK AN OBSERVATION.
      DO 20 ISTART = MONTH, N-12, 12
C         VALID VALUE?
      IF (X(ISTART).LE.XMIS) GO TO 20
C          VALUE IS ALWAYS TIED WITH ITSELF.
      NTIE=1
C         TRY EACH LATER MONTH.
      DO 30 IEND = ISTART+12, N, 12
C         VALID VALUE?
      IF (X(IEND).LE.XMIS) GO TO 30
C         COMPARE.
      NCOMP = NCOMP + 1
      INDEX = INDEX + 1
      YY = (X(IEND) - X(ISTART))/((IEND-ISTART)/12.)
      IF (YY.GT.0.0) NPLUS = NPLUS + 1
      IF (YY.LT.0.0) NMINUS = NMINUS + 1
      IF (YY.EQ.0.0) NTIE=NTIE+1
C        MARK VALUES THAT ARE TIED.
      IF (YY.EQ.0.0) WASTIE(IEND)=.TRUE.
C         SAVE ADJUSTED DIFFERENCES.
      Y(INDEX) = YY
   30 CONTINUE
C        UPDATE VARIANCE CORRECTION IF TIES OCCURED AND TIES WERE NOT COUNTED
C           BEFORE.
      IF (NTIE.NE.1.AND..NOT.WASTIE(ISTART)) FIXVAR=FIXVAR+
     &   NTIE*(NTIE-1.0)*(2.0*NTIE+5.0)/18.0
   20 CONTINUE
```

Figure B-1. Computer program for Seasonal Kendall procedures.

```
C          ACCUMULATE THIS MONTH'S RESULTS.
      NCOMPT = NCOMPT + NCOMP
      NMONTH = (1.0 + SQRT(1.0 + 8.0 * NCOMP))/2.0
      VARTOT = VARTOT + (1./18.)*NMONTH*(NMONTH-1.0)*(2.0*NMONTH+5.0)
   10 CONTINUE
C          DONE COMPARING.
      S = NPLUS - NMINUS
C          WERE THERE ANY VALID COMPARISONS?
      IF (NCOMPT.GT.0) GO TO 40
C          NO VALID COMPARISONS -- GO HOME EMTPY.
      TAU = 0.0
      ALPHA = 1.0
      SLOPE = 0.0
      RETURN
C          CALCULATE THE STATISTICS.
   40 CONTINUE
      VARTOT=VARTOT-FIXVAR
      TAU = S / NCOMPT
C          CONTINUITY CORRECTION.
      IF (S.GT.0.0) S = S - 1.
      IF (S.LT.0.0) S = S + 1.
C          COMPARE TO THE STANDARD NORMAL DISTRIBUTION. THE FUNCTION
C          CDFN RETURNS THE CUMULATIVE PROBABILITY AT DEVIATION Z IN THE
C          STANDARD NORMAL DISTRIBUTION.
      Z = S / SQRT(VARTOT)
      IF (Z.LE.0.0) ALPHA = 2.0 * CDFN(Z)
      IF (Z.GT.0.0) ALPHA = 2.0 * (1.0 - CDFN(Z))
C          SUBROUTINE VSRTA SORTS THE VECTOR Y OF LENGTH INDEX IN ASCENDING
C          ORDER IN PLACE.
      CALL VSRTA(Y,INDEX)
C          PICK MEDIAN.
      ODD = MOD(INDEX,2).EQ.1
      IF (ODD) YMED = Y((INDEX+1)/2)
      IF (.NOT.ODD) YMED = 0.5 * (Y(INDEX/2) + Y((INDEX/2)+1))
      SLOPE = YMED
      IF (SLOPE.NE.0.0) RETURN
C          ADJUST FOR THE FACT THAT TAU AND ALPHA MAY SAY THERE IS A SIGNIFICANT
C          TREND BUT THE ESTIMATE OF THE SLOPE IS ZERO DUE TO A TIE.
      IF (NMINUS.GT.NPLUS) SLOPE = -1.0E-30
      IF (NMINUS.LT.NPLUS) SLOPE = 1.0E-30
      RETURN
      END
```

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